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RELIABILITY ESTIMATING PROCEDURES FOR ELECTRIC AND THERMOCHEMICAL PROPULSION SYSTEMS

FINAL REPORT

VOL II

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This technical report has been reviewed and is approved for publication.

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The primary objective of this study was to develop a sound standardized basis for reliability comparisons of thermochemical and electric propulsion concepts applicable to Air Force satellite, spacecraft, and upper-stage mission requirements. A corollary objective was the identification of those propulsion system components which are currently the major contributors to propulsion system failures.

Nearly one hundred component level and failure mode level models were developed

in the course of the study. Constant and increasing failure rates were included to address erosion, wear, and fatigue failure, as well as random failures. Principal variables in these expressions included mission duration, operating time, and the number of operating cycles. For special cases (such as engine valves, injectors, thrust chambers) where design approaches were varied, the design life goals for the specific application were included as independent variables.

Inherent in the realiability modeling was a quantitative assessment of the uncertainty associated with each estimate. The log normal distribution was used as the uncertainty model for each component. The parameters characterizing the log normal distribution for each application were determined where possible from the scatter or statistical variance of reported failure rates for each component.

System level assessments were performed using functionally oriented fault trees. The functional approach was used to yield fault trees that are least affected by changes and revisions at the component level. System assessments were performed by aggregating the component reliability and uncertainty results through the fault tree logic using computer programs and approximation techniques which were modified or developed for this purpose.

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COMPUTER PROGRAMS

GENERAL

A family of computer programs provide the capability to examine life and uncertainty distributions at levels ranging from a specific failure mode of an individual device to a complete system of substantial complexity. All of the programs were written in the BASIC language (as implemented on the CDC Cybernet/Kronos time sharing system) in order to provide interactive-mode capabilities.

The family includes the following:

- COMP1 -- A program specifically tailored to 97 device types and/or failure modes included in the systems analyzed. For each device or failure mode, the program yields the median and 5 percent lower bound on reliability and the parameters of a beta distribution sharing those fractiles, for any desired point(s) in a mission.

- BETSB1 -- A program that accepts reliability/uncertainty descriptions (in beta-distribution form) for a group of components that are either identical or independent and have either a strictly series or a strictly parallel-redundant relationship. The output is a reliability/uncertainty description of the group in the form of moments of the distribution and the parameters of a beta distribution possessing those moment values.*

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*This program was developed under Contract No. N00123-74-C-1799 with the Naval Weapons Center, China Lake, California, and is described in NWC TP 5748, "Rocket-Ramjet Cost and Reliability Prediction Methodologies", July, 1975, the final technical report under that contract. Further discussion of the use of the Beta distribution is provided in Appendix B.

- BETSB2 -- Analogous to BETSB1, but designed for independent components in m-of-n redundant configuration.

- BETSB3 -- Also analogous to BETSB1, but designed for identical components in m-of-n redundant configuration.

- BETFTA -- This program provides the capabilities of BETSB1, expanded to allow concurrent analysis of groups of the four kinds (series-independent, series-identical, parallel-independent, parallel-identical). The input is in fault-tree terms; up to 20 levels and 100 events per level are allowed. Inhibit gates (with conditioning probabilities) also are accommodated. Lowest-level (component, failure mode) inputs are required to be in the form of beta-distribution parameters. M-of-n redundant configurations must be preprocessed (via BETSB2 or BETSB3, as appropriate); the result then may be treated as a basic event.

- BETAL1 -- This program is intended primarily for use at high levels (systems and major subsystems), although it may be used for any configuration whose elements are independent and in series. In addition to inputs as required for BETSB1, this program requires the cost of the next test for each element. The output, in addition to moments and parameters of a fitted beta distribution, includes identification of the element which, if tested next, would yield the maximum information gain (in terms of reduction in expected variance) per unit test cost; the corresponding amount of information gain, and that expected if the entire aggregate were tested next; and, via numerical integration of the fitted beta distribution, the 5, 10, and 20 percent lower bounds on the reliability of the aggregate. This program thus can be used for test planning/test resource allocation in advance of testing and, with minor manual intervention, as a real-time test planning tool.

Listings and short descriptions of each program follow.

PROGRAM DESCRIPTIONS

COMP1

This program will be described in somewhat greater detail than the others in view of its specificity, which will make it necessary to modify the program if components or failure rate estimates other than those provided are to be accommodated.

As noted above, program COMP1 is designed to calculate reliability descriptors for each of a fixed list of components/failure modes. Each component may be evaluated for any desired point during a mission with exposure measured in terms of mission time, operating time, number of pulses, or other measure, as appropriate for that component. The required measure(s) are identified by the program as the computation proceeds.

For most components, the required parameters are stored in final form. For some components, the parameters are calculated from design factors (e.g., design life) that must be input when requested. Each component/failure mode must be identified using the 2-4 character alphanumeric code indicated in Table 9 immediately following the COMP1 program listing.

Program output consists of the median and 5 percent lower bound of the reliability uncertainty distribution and of the parameters (alpha, beta) of an approximating beta distribution to those fractiles. Caveats also are displayed, as necessary, in the course of the interactive routine.

In some cases, the component life and uncertainty models are such that the 5 percent lower bound (RO in the program) coincides with or exceeds the median (R5) at extremely early and/or extremely late points in a mission. Coincidence also can occur due to computation resolution limitation when the reliability is very near 1 or 0. Most such occurrences have been anticipated and caveats as well as provisions to avoid program termination incorporated. Occasionally, error messages (e.g., "attempt to divide by zero" or "negative argument in log function") and program termination may be encountered.

The following description is keyed to the program listing in terms of blocks of statements:

30-127	The dual-subscript variables, W(I,J), are assigned values for subsequent use in decoding component labels and invoking the appropriate sequence of parameter assignment and exercise of life and uncertainty models.
201-209	The component label, a 2-4 character alphanumeric string, is requested, input, and translated into a unique I, J subscript pair. I is the display value of the first string character; J, the sum of the display values of the remaining characters.
210-252	C=W(I,J) is used to select the appropriate "ON...GOTO..." statement and thus the statement to which control is transferred. If "ZZ" has been input deliberately, or a string without valid interpretation has been input accidentally, the program terminates via a "No such component" message at 99998.
300-1234	Each group of statements begins with a statement number that is a multiple of 10. Each such group contains distribution parameters, requests for design information and special comments as needed, and "GOTO..." statements leading directly or indirectly to the appropriate life/uncertainty model.
2000-2876	Blocks of statements within this range deal with specific models as indicated below.
2000-2026	Exponential life distribution involving operating time.
2030-2056	Exponential life distribution involving "pressurized" time.
2060-2098	Exponential life distribution involving number of cycles.
2130-2154	Weibull life distribution (3-parameter) involving operating time.
2160-2190	Weibull life distribution (3-parameter) involving operating time and exponential life distribution involving operating time.

2200-2226	Exponential life distribution involving mission time.
2230-2268	Exponential life distribution involving mission time and exponential distribution involving number of cycles.
2270-2308	Exponential life distribution involving operating time and exponential distribution involving dormant time (obtained by subtracting operating time from mission time) and exponential distribution involving number of cycles.
2310-2366	Weibull life distribution (2-parameter) involving mission time and Weibull distribution (2-parameter) involving oeprating time and Weibull distribution (2-parameter) involving number of cycles.
2370-2384	Exponential life distribution involving operating time and exponential life distribution involving mission time.
2400-2430	Weibull life distribution (3-parameter) involving mission time and exponential distribution involving mission time.
2440-2480	Weibull life distribution (3-parameter) involving operating time and exponential distribution involving number of cycles and fixed fraction capable of success.
2500-2542	Weibull life distribution (3-parameter) involving operating time and Weibull distribution (2-parameter) involving number of cycles.
2550-2568	Weibull life distribution (2-parameter) involving operating time and Weibull distribution (2-parameter, shape parameter same) involving number of cycles and Weibull distribution (2-parameter, shape parameter fixed at 3.0) involving number of cold starts.
2580-2624	Weibull life distribution (2-parameter) involving operating time and Weibull distribution (2-parameter, shape parameter same) involving number of cycles and exponential distribution involving dormant time (obtained by subtracting operating time from mission time.

2640-2704	Exponential life distribution involving operating time and normal distribution (coefficient of variation fixed at 1/3) involving operating time and normal distribution (coefficient of variation fixed at 1/3) involving number of cycles.
2710-2746	Exponential life distribution involving mission time and normal distribution (coefficient of variation fixed at 0.15) involving mission time; failure by normal-distribution mechanism restricted to predefined subpopulation; special preset flags for apportionment among failure modes.
2750-2774	Lognormal life distribution (log standard deviation fixed at 0.3991) involving mission time to firing (mission time elapsed before actuation).
2810-2834	Exponential life distribution involving number of operating pulses and normal distribution involving number of operating pulses.
2860-2876	Exponential life distribution involving dormant time (obtained by subtracting operating time from mission time).
3000-3310	This series of statements provides approximations for fitting a beta distribution to the RO, R5 values. The following blocks of statements deal with matters of special interest as indicated.
3001-3003	In the approximations used, the dividing line between positive and negative values of beta corresponds to SO=0.89146, and computations are split accordingly.
3004-3009	If RO equals or exceeds R5, there are degeneracy (tail-crossing) problems as discussed previously. Appropriate messages are provided, and calculations are bypassed.
3010-3094	For negative values of beta, a piecewise-linear approximation is used. For beta less than -0.91, the approximation yields questionable alpha values as indicated by the programmed message.

3100-3310 For positive values of beta, the approximation used requires iterative calculations. The range for iteration is bounded, and a variable-increment procedures is used to limit the number of iterations required.

4000-4050 This block of statements embodies the infinite-series equivalent of the cumulative normal distribution. The series is truncated when the absolute value of the next term is on the order of 0.000001 or when 40 terms have been included; the series converges rapidly except at large distances from the mean. When the distance from the mean exceeds five standard deviations, the result is forced to 0.99999999 or 0.00000001 as appropriate.

The program also may be used, with minor modifications, to obtain the parameters of the fitted beta distribution for inputs consisting of $R_{.05}$ (R0) and $R_{.5}$ (R5). It is necessary only to overlay the following statements:

```
7 GOTO 5000
5000 PRINT "INPUT R.05, R.5 (0,0=END)"
5002 INPUT R0, R5
5004 IF R0=0 THEN 99999
5006 GOSUB 3000
5008 PRINT
5010 PRINT USING 2, R0, R5, A0, B0
5012 PRINT
5014 GOTO 5002
```

This modification will be referred to as BETAP 1.

BETSB1

This program, and those that follow, should be run in double precision mode if that feature is available (e.g., in IBM CALL-OS, where the corresponding command is "BASICL"). A reminder to that effect is printed following the "RUN" command. The feature is not available and not needed on CDC Cybernet/Kronos.

While this program is largely self-explanatory in execution, a description in terms of the inputs requested by the program may be helpful.

- TYPE OF INPUT (1-PARAM, 2=MEAN&VAR)
  As indicated, there is an option of input in terms of beta distribution parameters (alpha and beta, e.g., from COMP1) or in terms of the mean and variance of the beta distribution.

- HOW MANY COMPONENTS?
  The actual number of components (or failure modes) contained in the aggregate being examined. (For more than 10 components, it is necessary to add the statement 6 DIM A(**), B(**) where ** is a number exceeding the number of components by 1.)

- INDEPENDENT=1, IDENTICAL=2
  The response should be "2" only if all components not only have identical failure rate expectations and variances, but are of the same type (e.g., composition resistors of the same rating and resistance value and hence likely to come from the same manufacturing lot).

- SERIES=1, REDUNDANT=2
  Respond in accordance with the configuration being evaluated.

- VALUES
  Respond ***, ** using alpha and beta or mean and variance, as previously indicated.

BETSB2

From the user's standpoint, this program is similar to BETSB1; however, it handles only the case of independent components in m-of-n redundant configuration. The salient differences are:

- HOW MANY REQUIRED?
  Is an additional prompting statement; the response is the numerical value of m.

- Neither the series/redundant nor the independent/identical question will appear, the answer being implicit in the choice of this program.

- Twenty components are allowed by DIM statements at 140 and 142. A large number of good/bad state permutations are implicit; if that number is exceeded, a statement indicating the need for modification of the DIM statement at 142 will appear, as well as an indication of the numerical value required to be substituted.

BETSB3

This program handles identical components in m-of-n redundant configuration. The prompting statements are identical to those of BETSB2, except that no statement indicating need to extend array dimensions is provided; such extension usually will be unnecessary here.

BETFTA

This program is related to BETSB1, but allows combinations of identical/independent and series/redundant configurations and requires input in the form of a fault tree description. Input must be in parametric (alpha, beta) form and provided as a series of DATA statements. Immediately under under any logic "gate" events must be either all identical or all independent; the fault tree always can be restructured to meet this condition. Multiple input DATA sets may be provided; the program will continue until all DATA sets have been used. (This feature permits evaluation of the aggregate at a succession of points in a mission.) Key features of the program are described by a series of REM statements that may be displayed by commanding a listing starting with statement 80000 (in CDC Cybernet/Kronos BASIC, the command is LIST, 80000). An expanded discussion follows:

- HOW MANY LEVELS?
  The number of levels is equal to the number of events in the longest branch of the fault tree. (All logic gates within a branch, except inhibit gates, must be separated by events, which may be arbitrary if necessary.)

- EVENTS? (LOWEST FIRST) (SINGLE ASSUMED AT TOP)
  A series of inputs, consisting of the number of events at each level except the (single-event) top level, is required. Each input should be the total number of events at the appropriate level,

beginning with the lowest. (Note that not all branches need have events at all lower levels, and that there must be no gaps between the top level and the level at which each branch terminates.)

- DESTINATION
  Each event is implicitly defined by dual subscripts I, J, where I is the level and J is the number of the event under consideration at that level -- e.g., counting left-to-right. Thus, the first (e.g., leftmost) event at the third level is defined by the subscripts 3,1. The program will cause I,J to be printed; the correct response (DESTINATION) is the index J' of the connected event at level I+1.

- CONDITIONALS? (0.0=SKIP)
  A response should be provided for each inhibit gate in the form of the I,J subscripts of the event immediately <u>below</u> the inhibit gate. The next response should be the value of the probability associated with the inhibit gate. The sequence will continue until a 0,0 response (or any 0,J response) is given.

- GATE TYPES
  Each gate (other than inhibit gates) is identified by the I,J subscripts of the event immediately <u>above</u> it. The program will indicate each gate by printing the subscripts; the response should be 1 for an OR gate connecting independent events, 2 for an AND gate connecting independent events, 3 for an OR gate connecting identical events, 4 for an AND gate connecting identical events.

- Following completion of gate identification, the program automatically will read alpha and beta values for each input event from the DATA statements, which must be provided. Reading of data is in ascending order of levels and ascending value of the J subscript within each level, with automatic skipping of any event that is a "destination" (and thus has reliability values determined by lower-level events); the sequence of entries in DATA statements must correspond. For example, assume a three-level tree with two events at the lowest level and two at the second level, the first of which is the destination of the two lowest-level events. In this program, the alpha value of the I,J event is represented by T(I,J) and the beta val;ue by U(I,J). Support T(1,1)=3, U(1,1)=0, T(1.2)=9, U(1,2)=1.3, T(2,2)=11.5, U(2,2)=-.6. Then an appropriate set of DATA statements would be:

```
900 DATA 3,0,9,1.3
902 DATA 11.5,-.6
```

BETAL1

This program resembles BETSB1, but is intended for use in test planning and/or when calculation of lower bounds (5, 10, and 20 percent) is desired. Only series configurations of independent elements are accommodated; this restriction generally is met at high levels of aggregation (system, subsystems).

Most prompting statements are similar to those used in the BETSB series of programs or are self-explanatory. However, some statements are in the form of questions requiring yes/no answers. The response to such questions must be numeric (1 = yes, 0 = no). Some selected prompting statements and program features are discussed below.

- PERMIT NEGATIVE BETA?
  The beta distribution becomes J-shaped when either parameter is negative and U-shaped when both are negative. Negative parameter values arise when the uncertainty (variance) is relatively large, especially if the expected value is near 0 or 1, and are legitimate. However, the user may elect to allow only non-negative values of beta by responding "0"; if a negative value of beta then is encountered during computation, the program will automatically set beta equal to zero while retaining the expected value of the distrib ution, thus obtaining the largest variance admissible without negative values of beta.

- VALUES? (THIRD VALUE IS COST OF FIRST TEST)
  The required response is as in the BETSB programs, except that the cost of the first (next) test of each component also must be entered. This entry may be arbitrary when the program is used only to obtain lower bounds.

- DISPLAY COMPONENT VALUES?
  A positive response ("1") will cause parameters, moments, and assigned test costs to be displayed for all components. The displayed moments include expected value, E(P); second moment about the origin, E(P*P); and variance, V(P).

- CLOSURE
  The number displayed below this message is the total integral of the distribution over the interval 0,1. Numerical integration is used; if the displayed number differs substantially from 1.0, the validity of the displayed bounds is questionable.

- NO. DELV COST TOT COST NO. TESTS
  Under these headings there are displayed the identity of the component just "tested", the change in variance resulting from the "test", the cost of the "test", the accumulated cost of all component "tests", and the number of "tests", and the number of "tests" of the identified component. The change in variance (DELV) may be compared to the expected change, E(DELVAR), displayed under "FOR SYSTEM"; taking costs into account, one may elect not to CONTINUE. (Use of BETAL1 may be resumed subsequently, after one or more system "tests", using updated input values.) If one elects to CONTINUE, and opportunity is provided to adjust the cost of the next test of the same component (CHANGE NEXT COST?); if not, a display of the end-of-run status of all components is available.

As a before-the-fact test planning tool, the program uses "test" results on an expected-value basis; that is, a "test" increments the corresponding alpha by E(P) and beta by 1-E(P). When used in a real-time mode, one would increment alpha by 1 for a successful test and beta by 1 for a failing test; this incrementation would take place off-line, and the program exercised with the new values to identify the next component to be tested.

COMP1 Program Listing

```
2: #.######    #.######    ####.####    ##.####
4 PRINT "OUTPUT FORMAT IS"
6 PRINT "R.05        R.5        ALPHA        BETA"
8 DIM W(32,72)
30 W(12,19)=1
31 W(21,19)=2
32 W(12,1)=3
33 W(13,7)=4
34 W(2,2)=5
35 W(6,50)=6
36 W(20,20)=7
37 W(16,18)=8
38 W(16,20)=9
39 W(22,3)=10
40 W(22,12)=11
41 W(19,1)=12
42 W(19,16)=13
43 W(6,12)=14
44 W(8,3)=15
45 W(9,9)=16
46 W(14,9)=17
47 W(14,22)=17
48 W(14,3)=15
49 W(4,3)=18
50 W(22,8)=19
51 W(13,19)=20
52 W(8,54)=21
53 W(21,59)=22
54 W(13,27)=23
55 W(14,16)=24
56 W(3,19)=25
57 W(22,38)=26
58 W(22,37)=27
59 W(22,25)=28
60 W(20,7)=29
61 W(16,35)=30
62 W(22,30)=31
63 W(16,21)=32
64 W(6,21)=30
65 W(6,51)=33
66 W(6,6)=34
```

```
67  w(6,15)=35
68  w(2,34)=36
69  w(2,25)=37
70  w(2,37)=38
71  w(26,3)=39
72  w(19,13)=40
73  w(3,2)=41
74  w(3,22)=42
75  w(3,33)=43
76  w(3,26)=44
77  w(5,31)=45
78  w(6,31)=46
79  w(6,17)=47
80  w(13,47)=48
81  w(13,5)=49
82  w(3,12)=50
83  w(12,25)=51
84  w(8,25)=52
85  w(19,19)=53
86  w(19,3)=54
87  w(9,16)=55
88  w(16,2)=56
89  w(9,49)=57
90  w(9,37)=58
91  w(9,46)=59
92  w(18,14)=60
93  w(18,23)=61
94  w(3,37)=62
95  w(3,25)=63
96  w(3,38)=64
97  w(5,37)=65
98  w(5,25)=66
99  w(5,38)=67
100 w(5,53)=68
101 w(2,39)=69
102 w(2,40)=70
103 w(2,48)=71
104 w(2,49)=72
105 w(2,41)=73
106 w(2,42)=74
107 w(6,32)=75
108 w(6,23)=76
109 w(5,28)=77
110 w(9,29)=78
111 w(9,19)=79
112 w(9,31)=80
113 w(9,8)=81
114 w(3,18)=82
115 w(3,21)=83
116 w(3,6)=84
117 w(20,16)=85
118 w(20,5)=86
119 w(18,22)=87
120 w(8,29)=88
121 w(20,37)=89
```

```
122 W(5,60)=90
123 W(2,4)=91
124 W(19,47)=92
125 W(26,26)=0
126 W(14,19)=93
127 W(9,50)=94
200 PRINT
201 PRINT "COMPONENT CODE?(ZZ=END)"
202 INPUT A$
203 CHANGE A$ TO U
204 J=0
205 FOR I=2 TO U(0)+.1
206 J=J+U(I)
207 NEXT I
208 I=U(1)
209 C=W(I,J)
210 IF C<1 THEN 99998
211 IF C>10 GOTO 214
212 ON C GOTO 300,310,320,330,340,350,360,370,380,390
214 IF C>20 GOTO 218
216 ON (C-10) GOTO 400,410,420,430,440,450,460,470,480,490
218 IF C>30 GOTO 222
220 ON (C-20) GOTO 500,510,520,530,540,550,560,570,580,590
222IF C>40 GOTO226
224 ON (C-30) GOTO 600,610,620,630,640,650,660,670,680,690
226 IF C>50 GOTO 230
228 ON (C-40) GOTO 700,710,720,730,740,750,760,770,780,790
230 IF C>60 GOTO 234
232 ON (C-50) GOTO 800,810,820,830,840,850,860,870,880,890
234 IF C>70 GOTO 238
236 ON (C-60) GOTO 900,910,920,930,940,950,960,970,980,990
238 IF C>80 GOTO 242
240 ON (C-70) GOTO 1000,1010,1020,1030,1040,1050,1060,1070,
                                                  1080,1090
242 IF C>90 GOTO 246
244 ON (C-80) GOTO 1100,1110,1120,1130,1140,1150,1160,1170,
                                                  1180,1190
246 IF C>100 THEN 250
248 ON (C-90) GOTO 1200,1210,1220,1230
250 PRINT "NO SUCH COMPONENT"
252 GOTO 99999
300 F(1,1)=5.3E-7
301 F(1,2)=8.03E-6
309 GOTO 2000
310 F(1,1)=2.91E-7
311 F(1,2)=5.3E-6
312 GOTO 2000
320 F(1,1)=1.78E-6
321 F(1,2)=1.79E-5
322 GOTO 2000
330 F(1,1)=1.86E-6
331 F(1,2)=1.85E-5
332 GOTO 2000
340 F(5,1)=1.04E-7
```

```
341 F(5,2)=3.12E-7
342 GØTØ 2030
350 F(5,1)=9.1E-9
351 F(5,2)=3.23E-7
352 GØTØ 2030
360 F(5,1)=8.6E-8
361 F(5,2)=8.7E-7
362 GØTØ 2030
370 F(5,1)=4.3E-8
371 F(5,2)=4.35E-7
372 GØTØ 2030
380 PRINT "SAME AS PR"
381 GØTØ 370
390 F(1,1)=2.59E-7
391 F(1,2)=3.185E-6
392 GØTØ 2000
400 F(1,1)=1.25E-6
401 F(1,2)=9.96E-6
402 F(2,1)=1.87E-6
403 F(2,2)=1.27E-5
404 GØTØ 2060
410 F(3,1)=2.36E-9
411 F(3,2)=2.23E-8
412 GØTØ 2100
420 PRINT "SAME AS SA"
421 GØTØ 410
430 F(1,1)=7.55E-8
431 F(1,2)=.2E-6
432 GØTØ 2000
440 F(1,1)=4.67E-6
441 F(1,2)=67.7E-6
442 GØTØ 2000
450 F(6,1)=4.4E9
451 F(6,2)=3.4E8
452 B6=2
453 A6=0
454 GØTØ 2130
460 PRINT "CLØG & LEAK CØMBINED"
461 PRINT "( TØ SEPARATE, USE VC AND VL )"
462 F(1,1)=3.84E-6
463 F(1,2)=1.2735E-5
464 F(2,1)= 2.59E-7
465 F(2,2)=1.27E-5
466 GØTØ 2060
470 F(1,1)=0.38E-6
471 F(1,2)=5.8E-6
472 F(6,1)=1.767E12
473 F(6,2)=1.146E11
474 B6=3
475 A6=5000
476 GØTØ 2160
480 F(1,1)=4E-7
481 F(1,2)=2.73E-6
482 GØTØ 2000
490 F(4,1)=1.66E-7
491 F(4,2)=1.57E-6
492 GØTØ 2200
```

```
500 F(4,1)=2.09E-8
501 F(4,2)=1.69E-7
502 GØTØ 2200
510 B9=0
511 F(4,1)=9.4E-7
512 F(4,2)=4.63E-6
513 F(7,1)=1E4
514 F(9,1)=.038
515 F(9,2)=.09
516 GØTØ 2710
520 F(6,1)=1.3E9
521 F(6,2)=7.306E7
522 B6=2
523 A6=6000
524 F(1,1)=2.7E-6
525 F(1,2)=56.8E-6
526 GØTØ 2160
530 F(1,1)=3.7E-5
531 F(1,2)=5.41E-5
532 GØTØ 2000
540 F(4,1)=1.885E-6
541 F(4,2)=6.788E-6
542  GØTØ 2200
550 F(1,1)=7.154E-7
551 F(1,2)=8.557E-6
552 GØTØ 2000
560 PRINT "SAME AS VVP"
561 GØTØ 550
570 PRINT "SAME AS VVP"
571 GØTØ 550
580 B9=1
581 F(2,1)=9.7E-9
582 F(2,2)=7E-8
583 GØTØ 511
590 PRINT "PCIL & FU ALIKE"
591 B9=2
592 GØTØ 511
600 F(1,1)=4E-7
601 F(1,2)=2.73E-6
602 GØTØ 2000
610 F(4,1)=4.85E-8
611 F(4,2)=1.877E-7
612 GØTØ 2200
620 F(4,1)=1.94E-8
621 F(4,2)=1.4E-7
622 GØTØ 2200
630 F(6,1)=2.95E9
631 F(6,2)=1.9E8
632 B6=2
633 A6=0
634 GØTØ 2130
640 F(4,1)=1.08E-8
641 F(4,2)=1.66E-7
642 GØTØ 2200
650 F(4,1)= 1.8E-9
651 F(4,2)=5.2E-8
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652 GOTO 2200
660 F(4,1)=6.5E-8
661 F(4,2)=7.66E-7
662 GOTO 2200
670 PRINT "SAME AS BVC"
671 GOTO 660
680 F(4,1)=5E-9
681 F(4,2)=5.8E-8
682 GOTO 2200
690 F(1,1)=7.55E-8
691 F(1,2)=2E-7
692 GOTO 2000
700 F(1,1)=4.85E-8
701 F(1,2)=1.877E-7
702 GOTO 2000
710 F(4,1)=1.302E-6
711 F(4,2)=4.658E-6
712 GOTO 2200
720 F(1,1)=2.3E-7
721 F(1,2)=6.14E-6
722 GOTO 2000
730 F(1,1)=6.5E-7
731 F(1,2)=9.47E-6
732 GOTO 2000
740 F(6,1)=4.9E9
741 F(6,2)=3.4E8
742 A6=0
743 B6=2
744 GOTO 2130
750 F(2,1)=3.5E-8
751 F(2,2)=1.11E-6
752 F(4,1)=3.[illegible]E-8
753 F(4,2)=1.01E-6
754 GOTO 2230
760 F(1,1)=3.8E-7
761 F(1,2)=5.8E-6
762 F(2,1)=2E4
763 F(2,2)=1E4
764 F(7,1)=1.85E4
765 F(7,2)=9.25E3
766 GOTO 2640
770 PRINT "APPLIED VOLTS/RATED VOLTS=?"
771 INPUT B4
772 F(2,1)=B4*5E-12*.224
773 F(2,2)=B4*5E-12*3.855
774 F(7,1)=(B4↑(-7.5))*6.07E3
775 F(7,2)=(B4↑(-7.5))*1.17E3
776 B7=.165
777 GOTO 2810
780 F(3,2)=2E-9
781 F(3,1)=2E-9
782 GOTO 2100
790 F(1,2)=2E-6
791 F(1,1)=1.42E-6
792 GOTO 2000
```

```
800 F(1,2)=3.01-6
801 F(1,1)=1.247E-6
802 GØTØ 2000
810 F(1,2)=2.62E-6
811 F(1,1)=1.56E-6
812 GØTØ 2000
820 F(1,2)=2.85E-6
821 F(1,1)=1.15E-6
822 GØTØ 2000
830 F(1,2)=2.5E-6
831 F(1,1)=0.198E-6
832 GØTØ 2000
840 B7=.2
841 F(2,1)=2E-10
842 F(2,2)=2E-9
843 F(7,1)=2.4E7
844 F(7,2)=1.2E7
845 GØTØ 2810
850 F(1,2)=1.48E-6
851 F(1,1)=0.826E-6
852 GØTØ 2000
860F(2,1)=3.03E-9
861 F(2,2)=1.08E-7
862 F(4,1)=3.6E-9
863 F(4,2)=1.04E-7
864 GØTØ 2230
870 F(2,1)=9.1E-9
871 F(2,2)=3.24E-7
872 F(4,1)=1.08E-8
873 F(4,2)=3.12E-7
874 GØTØ 2230
880 F(4,1)=1.8E-9
881 F(4,2)=5.2E-8
882 GØTØ2200
890 F(5,1)=1.143E-6
891 F(5,2)=6.6E-6
892 F(1,1)=2.42E-4
893 F(1,2)=2.04E-3
894 F(2,1)=2.24E-6
895 F(2,2)=1.2E-5
896 GØTØ 2270
900 F(5,1)=1.7E-6
901 F(5,2)=9.9E-6
902 F(1,1)=3.63E-4
903 F(1,2)=3.06E-3
904 F(2,1)=3.36E-6
905 F(2,2)=1.8E-5
906 GØTØ 2270
910 F(2,1)=6.6E-6
911 F(2,2)=2.6E-4
912 F(4,1)=3.8E-7
913 F(4,2)=2.93E-6
914 GØTØ 2230
920 PRINT "SAME AS CVØ"
921 GØTØ 910
```

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930 F(2,1)=1.32E-5
931 F(2,2)=5.15E-4
932 F(4,1)=7.6E-7
933 F(4,2)=5.85E-6
934 GØTØ 2230
940 PRINT "DESIGN CYCLE LIFE,ØP. LIFE,MISSIØN DURATIØN"
941 INPUT B2,B1,B4
942 B6=1.5
943 F(2,1)=((B2/2)↑.5)/2.5E-8
944 F(2,2)=((B2/2)↑.5)/8E-8
945 F(1,1)=((B1/2)↑.5)/5.5E-6
946 F(1,2)=((B1/2)↑.5)/3.32E-5
947 F(4,1)=((B4/2)↑.5)/4.48E-8
948 F(4,2)=((B4/2)↑.5)/3.63E-7
949 GØTØ 2310
950 PRINT "DESIGN CYCLE LIFE,ØP. LIFE,MISSIØN DURATIØN"
951 INPUT B2,B1,B4
952 B6=1.5
953 F(2,1)=((B2/2)↑.5)/7.5E-8
954 F(2,2)=((B2/2)↑.5)/2.4E-7
955 F(1,1)=((B1/2)↑.5)/1.65E-5
956 F(1,2)=((B1/2)↑.5)/9.96E-5
957 F(4,1)=((B4/2)↑.5)/1.34E-7
958 F(4,2)=((B4/2)↑.5)/1.09E-6
959 GØTØ 2310
960 PRINT "DESIGN CYCLE LIFE, ØP. LIFE, MISSIØN DURATIØN"
961 INPUT B2,B1,B4
962 B6=1.5
963 F(2,1)=((B2/2)↑.5)/1.5E-7
964 F(2,2)=((B2/2)↑.5)/4.8E-7
965 F(1,1)=((B1/2)↑.5)/3.03E-5
966 F(1,2)=((B1/2)↑.5)/1.83E-4
967 F(4,1)=((B4/2)↑.5)/2.48E-7
968 F(4,2)=((B4/2)↑.5)/2E-6
969 GØTØ 2310
970 F(1,1)=2.75E-6
971 F(1,2)=1.66E-5
972F(4,1)=2.24E-8
973 F(4,2)=1.8E-7
974 GØTØ 2370
980 A6=2.2E4
981 B6=1.2
982 F(6,1)=1.54E6
983 F(6,2)=5E5
984 F(4,1)=4.74E-7
985 F(4,2)=1.48E-6
986 GØTØ 2400
990 PRINT "SAME AS REF1"
991 GØTØ 980
1000 A6=1.3E4
1001 B6=2
1002 GØTØ 982
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1010 PRINT "SAME AS BE01"
1011 GOTO 1000
1020 A6=4.3E4
1021 B6=1.2
1022 F(6,1)=4E7
1023 F(6,2)=2.42E6
1024 F(4,1)=2.84E-8
1025F(4,2)=4.7E-7
1026 GOTO 2400
1030 PRINT "SAME AS BM1"
1031 GOTO 1020
1040 F(4,1)=1.07E-8
1041 F(4,2)=1.66E-7
1042 GOTO 2200
1050 F(6,1)=2.95E8
1051 F(6,2)=1.9E7
1052 A6=0
1053 B6=1.5
1054 GOTO 2130
1060 PRINT "THRUSTER CYCLES & OP.TIME"
1061 F(2,1)=3.57E-8
1062 F(2,2)=4.46E-7
1063 F(6,1)=6.3E12
1064 F(6,2)=1.64E12
1065 A6=0
1066 B6=3
1067 F(9,1)=0.99
1068 F(9,2)=.977
1069 GOTO 2440
1070 A6=0
1071 B6=1.5
1072 PRINT "DESIGN OP. LIFE=?"
1073 INPUT B1
1074 F(6,1)=(.2*B1)↑.5/4.71E-7
1075 F(6,2)=(.2*B1)↑.5/1.1E-6
1076 GOTO 2130
1080 A6=0
1081 B6=1.5
1082 PRINT "DESIGN CYCLE LIFE, OP.LIFE?"
1083 INPUT B2,B1
1084 F(6,1)=(.2*B1)↑.5/4.71E-7
1085 F(6,2)=(.2*B1)↑.5/1.1E-6
1086 F(2,1)=(.2*B2)↑.5/1.67E-8
1087 F(2,2)=(.2*B2)↑.5/1E-7
1088 GOTO 2500
1090 F(4,1)=2.77E-9
1091 F(4,2)=1.65E-8
1092 GOTO 2200
1100 PRINT "SAME AS I''"
1101 GOTO 1090
1102 PRINT"DESIGN CYC   LIFE,DESIGN COLD STARTS,OP.LIFE?"
1104 INPUT B2,B3,B1
1106 B6=1.5
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1108 F(1,1)=(.2*B1)↑.5/1.53E-6
1110 F(1,2)=(.2*B1)↑.5/9.2E-6
1112 F(2,1)=(.2*B2)↑.5/4.9E-8
1114 F(2,2)=(.2*B2)↑.5/3.5E-7
1116 IF B3=0 THEN 2550
1117 F(3,1)=(.2*B3)↑2/6.2E-6
1118 F(3,2)=(.2*B3)↑2/3.72E-5
1119 GOTO 2550
1120 PRINT "DESIGN CYCLE LIFE,COLD START LIFE,OP. LIFE?"
1121 INPUT B2,B3,B1
1122 B6=2
1123 F(2,1)=.5*B2/2.8E-6
1124 F(2,2)=.5*B2/1.7E-5
1125 F(1,1)=.5*B1/7.6E-5
1126 F(1,2)=.5*B1/4.6E-4
1127 IF B3=0 THEN 2550
1128 F(3,1)=(.2*B3)↑2/6.2E-6
1129 F(3,2)=(.2*B3)↑2/3.72E-5
1130 GOTO 2550
1131 F(1,2)=3.5E-8
1132 F(1,1)=4.9E-9
1134 GOTO 2860
1140 PRINT "DESIGN CYCLE LIFE,OP.LIFE?"
1141 INPUT B2,B1
1142 F(2,1)=(.5*B2)↑.5/9.7E-9
1143 F(2,2)=(.5*B2)↑.5/7E-8
1144 F(1,1)=(.5*B1)↑.5/1.02E-7
1145 F(1,2)=(.5*B1)↑.5/6.1E-7
1148 B6=1.5
1149 GOTO 2580
1150 PRINT "DESIGN CYCLE LIFE,OP.LIFE?"
1151 PRINT "(CYCLES=PULSES)"
1152 INPUT B2,B1
1153 F(2,1)=(.5*B2)↑.5/2.7E-9
1154 F(2,2)=(.5*B2)↑.5/7E-9
1155 F(1,1)=(.5*B1)↑.5/3E-5
1156 F(1,2)=(.5*B1)↑.5/6.35E-5
1157 B6=1.5
1158 GOTO 2580
1160 F(2,1)=1.9E-6
1161 F(2,2)=8.34E-6
1162 F(4,1)=3E-7
1163 F(4,2)=1.23E-5
1164 GOTO 2230
1170 F(2,1)=3.45E-8
1171 F(2,2)=9.26E-7
1172 F(6,1)=1.9E15
1173 F(6,2)=7.07E13
1174 F(9,1)=0.96
1175 F(9,2)=.91
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1176 A6=0
1177 B6=3.5
1178 GOTO 2440
1180 PRINT "DESIGN OP. LIFE=?"
1181 INPUT B1
1182 F(6,1)=(.1*B1)↑1.5/1.11E-7
1183 F(6,2)=(.1*B1)↑1.5/6.62E-7
1184 A6=0
1185 B6=2.5
1186 GOTO 2130
1190 PRINT "REL=1.0 UNTIL FIRING REQUIRED"
1191 F(7,1)=7
1192 F(7,2)=5
1193 GOTO 2750
1199 PRINT "ASSESSED AS BACK-UP TO RELIEF VALVE ONLY"
1200 PRINT"NEGLIGIBLE IMPACT AT SYSTEM LEVEL"
1201 PRINT "(USE REL=1.0 IF NO OTHER DATA)"
1202 GOTO 200
1210 F(4,1)=9.75E-9
1211 F(4,2)=1.66E-7
1212 GOTO 2200
1220 F(4,1)=3.89E-10
1221 F(4,2)=2.8E-9
1222 GOTO 2200
1230 F(2,1)=1.82E-8
1231 F(2,2)=6.48E-7
1232 F(4,1)=1.98E-8
1233 F(4,2)=6.24E-7
1234 GOTO 2230
2000 PRINT "OPTIME=? (0=END)"
2002 INPUT T(1)
2004 IF T(1)<=0 THEN 200
2006 R0=EXP(-F(1,2)*T(1))
2008 R5=EXP(-F(1,1)*T(1))
2020 GOSUB 3000
2022 PRINT USING 2,R0,R5,A0,B0
2024 PRINT "OPTIME=?"
2026 GOTO 2002
2030 PRINT "PRESS. TIME=? (0=END)"
2032 INPUT T(5)
2034 IF T(5)<=0 THEN 200
2036 R0=EXP(-F(5,2)*T(5))
2038 R5=EXP(-F(5,1)*T(5))
2050 GOSUB 3000
2052 PRINT USING 2,R0,R5,A0,B0
2054 PRINT "PRESS. TIME=?"
2056 GOTO 2032
2060 PRINT " INPUT OPTION"
2062 PRINT "1= FIXED CYCLES/OP.HR., 2=SEPARATE"
2064 INPUT F(9,9)
2066 IF F(9,9)=2 THEN 2074
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2068 PRINT "CYCLES/ØP.HR.=?"
2070 INPUT F(9,8)
2072 GØTØ 2080
2074 PRINT "CYCLES =? (O=END)"
2076 INPUT T(2)
2078 IF T(2)<=0 THEN200
2080 PRINT "ØPTIME=? (O=END)"
2082 INPUT T(1)
2083 IF T(1)<=0 THEN 200
2084 IF F(9,9)=2 THEN 2088
2086 T(2)=F(9,8)*T(1)
2088 R0=EXP((-F(1,2)*T(1))-(F(2,2)*T(2)))
2090 R5=EXP((-F(1,1)*T(1))-(F(2,1)*T(2)))
2092 GØSUB 3000
2094 PRINT USING 2,R0,R5,A0,B0
2096 IF F(9,9)=2 THEN 2074
2098 GØTØ 2080
2100 PRINT "NØ. CYCLES =? (O=END)"
2102 INPUT T(3)
2104 IF T(3)<=0 THEN 200
2106 R0=EXP(-F(3,2)*T(3))
2108 R5=EXP(-F(3,1)*T(3))
2120 GØSUB 3000
2122 PRINT USING 2,R0,R5,A0,B0
2124 PRINT "NØ. CYCLES=?"
2126 GØTØ 2102
2130 PRINT "ØPTIME=? (O=END)"
2132 INPUT T(6)
2134 IF T(6)<=0 THEN 200
2136 IF T(6)<=A6 THEN 2152
2138 T(6)=(T(6)-A6)↑B6
2140 R0=EXP(-T(6)/F(6,2))
2142 R5=EXP(-T(6)/F(6,1))
2144 GØSUB 3000
2146 PRINT USING 2,R0,R5,A0,B0
2148 PRINT "ØPTIME=?"
2150 GØTØ 2132
2152 PRINT "RELIABILITY=1 (ØP.TIME<=GUARANTEE)"
2154 GØTØ 2130
2160 PRINT "ØPTIME=? (O=END)"
2162 INPUT T(1)
2164 IF T(1)<=0 THEN 200
2166 T(6)=T(1)
2168 R0=1
2170 R5=1
2172 IF T(6)<=A6 THEN 2180
2174 T(6)=(T(6)-A6)↑B6
2176 R0=EXP(-T(6)/F(6,2))
2178 R5=EXP(-T(6)/F(6,1))
```

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2180 R0=R0*EXP(-F(1,2)*T(1))
2182 R5=R5*EXP(-F(1,1)*T(1))
2184 GØSUB 3000
2186 PRINT USING 2,R0,R5,A0,B0
2188 PRINT"ØPTIME=?"
2190 GØTØ 2162
2200 PRINT "MISSIØN TIME=? (0=END)"
2202 INPUT T(4)
2204 IF T(4)<=0 THEN 200
2206 R0=EXP(-F(4,2)*T(4))
2208 R5=EXP(-F(4,1)*T(4))
2220 GØSUB 3000
2222 PRINT USING 2,R0,R5,A0,B0
2224 PRINT "MISSIØN TIME=?"
2226 GØTØ 2202
2230 PRINT "INPUT ØPTIØN"
2232 PRINT "1=FIXED CYCLES/MISSIØN HR., 2=SEPARATE"
2234 INPUT F(9,9)
2236 IF F(9,9)=2 THEN 2244
2238 PRINT "CYCLES/MISSIØN HR.=?"
2240 INPUT F(9,8)
2242 GØTØ 2250
2244 PRINT "CYCLES=? (0=END)"
2246 INPUT T(2)
2248 IFT(2)<=0 THEN 200
2250 PRINT "MISSIØN TIME =? (0=END)"
2252 INPUT T(4)
2253 IF T(4)<=0 THEN 200
2254 IF F(9,9)=2 THEN 2258
2256 T(2)=F(9,8)*T(4)
2258 R0=EXP((-F(4,2)*T(4))-(F(2,2)*T(2)))
2260 R5=EXP((-F(4,1)*T(4))-(F(2,1)*T(2)))
2262 GØSUB 3000
2264 PRINT USING 2,R0,R5,A0,B0
2266 IF F(9,9)=2 THEN 2244
2268 GØTØ 2250
2270 PRINT"INPUT ØPTIØN"
2272 PRINT "1= FIXED CYCLES/ØP.HR., 2=SEPARATE"
2274 INPUT F(9,9)
2276 IF F(9,9)=2 THEN 2284
2278 PRINT "CYCLES/ØP.HR=?"
2280 INPUT F(9,8)
2282 GØTØ 2290
2284 PRINT "CYCLES=? (0=END)"
2286 INPUT T(2)
2288 IF T(2)<=0 THEN 200
2290 PRINT "MISSIØN TIME,ØP. TIME (0=END)"
2292 INPUT T(4),T(1)
2293 IF T(4)<=0 THEN 200
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2294 IF F(9,9)=2 THEN 2298
2296 T(2)=F(9,8)*T(1)
2298 R0=EXP((-F(1,2)*T(1))-(F(5,2)*(T(4)-T(1)))-(F(2,2)*T(2)))
2300 R5=EXP((-F(1,1)*T(1))-(F(5,1)*(T(4)-T(1)))-(F(2,1)*T(2)))
2302 GØSUB 3000
2304 PRINT USING 2,R0,R5,A0,B0
2306 IF F(9,9)=2 THEN 2284
2308 GØTØ 2290
2310 PRINT "INPUT ØPTIØN"
2312 PRINT "1=FIXED CYCLES/ØP.HR.,2=SEPARATE"
2314 INPUT F(9,9)
2328 IF F(9,9)=2 THEN 2336
2330 PRINT "CYCLES/ØP.HR.=?"
2332 INPUT F(9,8)
2334 GØTØ 2342
2336 PRINT "CYCLES=? (0=END)"
2338 INPUT T(2)
2340 IF T(2)<=0 THEN 200
2342 PRINT "MISSIØN TIME,ØP.TIME(0,0=END)"
2344 INPUT T(4),T(1)
2346 IF T(4)<=0 THEN 200
2348 IF F(9,9)=2 THEN 2352
2350 T(2)=F(9,8)*T(1)
2352 R0=T(2)↑B6/F(2,2)+T(1)↑B6/F(1,2)+T(4)↑B6/F(4,2)
2354 R0=EXP(-R0)
2356 R5=T(2)↑B6/F(2,1)+T(1)↑B6/F(1,1)+T(4)↑B6/F(4,1)
2358 R5=EXP(-R5)
2360 GØSUB 3000
2362 PRINT USING 2,R0,R5,A0,B0
2364 IF F(9,9)=2 THEN 2336
2366 GØTØ 2342
2370 PRINT "MISSIØN TIME, ØPTIME=? (0,0=END)"
2372 INPUT T(4),T(1)
2374 IF T(4)<=0 THEN 200
2376 R0=EXP(-(F(1,2)*T(1))-F(4,2)*T(4))
2378 R5=EXP(-(F(1,1)*T(1))-F(4,1)*T(4))
2380 GØSUB 3000
2382 PRINT 2,R0,R5,A0,B0
2384 GØTØ 2370
2400 PRINT "MISSIØN TIME=? (0=END)"
2402 INPUT T(4)
2404 IF T(4)<=0 THEN 200
2406 T(6)=T(4)
2408 R0=1
2410 R5=1
2412 IF T(6)<=A6 THEN 2420
2414 T(6)=(T(6)-A6)↑B6
2416 R0=EXP(-T(6)/F(6,2))
2418 R5=EXP(-T(6)/F(6,1))
```

```
2420 RO=RO*EXP(-F(4,2)*T(4))
2422 R5=R5*EXP(-F(4,1)*T(4))
2424 GØSUB 3000
2426 PRINT USING 2,RO,R5,AO,BO
2428 PRINT "MISSIØN TIME=?"
2430 GØTØ 2402
2440 PRINT " INPUT ØPTIØN"
2442 PRINT"1=FIXED CYCLES/ØP.HR., 2=SEPARATE"
2444 INPUT F(9,9)
2446 IF F(9,9)=2 THEN 2454
2448 PRINT "CYCLES/ØP.HR.=?"
2450 INPUT F(9,8)
2452 GØTØ 2460
2454 PRINT "CYCLES=? (O=END)"
2456 INPUT T(2)
2458 IF T(2)<=0 THEN 200
2460 PRINT "ØPTIME=? (O=END)"
2462 INPUT T(1)
2463 IF T(1)<=0 THEN 200
2464 IF F(9,9)=2 THEN 2468
2466 T(2)=F(9,8)*T(1)
2468 T(6)=(T(1)-A6)↑B6
2470 RO=F(9,2)*EXP(-(F(2,2)*T(2))-T(6)/F(6,2))
2472 R5=F(9,1)*EXP(-(F(2,1)*T(2))-T(6)/F(6,1))
2474 GØSUB 3000
2476 PRINT USING 2,RO,R5,AO,BO
2478 IF F(9,9)=2 THEN 2454
2480 GØTØ 2460
2500 PRINT "INPUT ØPTIØN"
2502 PRINT "1=FIXED CYCLES/ØP.HR., 2=SEPARATE"
2504 INPUT F(9,9)
2506 IF F(9,9)=2 THEN 2514
2508 PRINT "CYCLES/ØP.HR.=?"
2510 INPUT F(9,8)
2512 GØTØ 2520
2514 PRINT "CYCLES=? (O=END)"
2516 INPUT T(2)
2518 IF T(2)<=0 THEN 200
2520 PRINT "ØPTIME=? (O=END)"
2522 INPUT T(1)
2523 IF T(1)<=0 THEN 200
2524 IF F(9,9)=2 THEN 2528
2526 T(2)=F(9,8)*T(1)
2528 T(6)=(T(1)-A6)↑B6
2530 T(2)=T(2)↑B6
2532 RO=EXP(-(T(6)/F(6,2))-T(2)/F(2,2))
2534 R5=EXP(-(T(6)/F(6,1))-T(2)/F(2,1))
2536 GØSUB 3000
2538 PRINT USING 2,RO,R5,AO,BO
```

```
2540 IF F(9,9)=2 THEN 2514
2542 GØTØ 2520
2550 PRINT "CYCLES,CØLD STARTS,ØP. TIME, (T=0=END)"
2552 INPUT T(2),T(3),T(1)
2553 IF T(1)<=0 THEN 200
2554 T(2)=T(2)↑B6
2556 T(1)=T(1)↑B6
2558 IF B3=0 THEN 2562
2560 R0=EXP(-(T(2)/F(2,2))-T(3)/F(3,2)-T(1)/F(1,2))
2561 R5=EXP(-(T(2)/F(2,1))-T(3)/F(3,1)-T(1)/F(1,1))
2562 R0=EXP(-(T(2)/F(2,2))-T(1)/F(1,2))
2563 R5=EXP(-(T(2)/F(2,1))-T(1)/F(1,1))
2564 GØSUB 3000
2566 PRINT USING 2,R0,R5,A0,B0
2568 GØTØ 2550
2580 PRINT "INPUT ØPTIØN"
2582 PRINT "1=FIXED CYCLES/ØP.HR., 2=SEPARATE"
2584 INPUT F(9,9)
2586 IF F(9,9)=2 THEN 2594
2588 PRINT "CYCLES/ØP.HR.=?"
2590 INPUT F(9,8)
2592 GØTØ 2600
2594 PRINT "CYCLES =? (0=END)"
2596 INPUT T(2)
2598 IF T(2)<=0 THEN 200
2600 PRINT "MISSIØN TIME,ØP. TIME (0,0=END)"
2602 INPUT T(4),T(1)
2603 IF T(4)<=0 THEN 200
2604 IF F(9,9)=2 THEN 2608
2606 T(2)=F(9,8)*T(1)
2608 T(2)=T(2)↑B6
2612 T(1)=T(1)↑B6
2614 R0=EXP(-T(1)/F(1,2)-T(2)/F(2,2))
2616 R5=EXP(-T(1)/F(1,1)-T(2)/F(2,1))
2618 GØSUB 3000
2620 PRINT USING 2,R0,R5,A0,B0
2622 IF F(9,9)=2 THEN 2594
2624 GØTØ 2600
2640 PRINT "INPUT ØPTIØN"
2642 PRINT "1=FIXED CYCLES/ØP.HR.,2=SEPARATE"
2644 INPUT F(9,9)
2646 IF F(9,9)=2 THEN 2654
2648 PRINT "CYCLES/ØP.HR.=?"
2650 INPUT F(9,8)
2652 GØTØ 2660
2654 PRINT "CYCLES=?(0=END)"
2656 INPUT T(2)
2658 IF T(2)<=0 THEN 200
2660 PRINT "ØPTIME=?(0=END)"
```

```
2662 INPUT T(1)
2664 IF T(1)<=0 THEN 200
2666 IF F(9,9)=2 THEN 2670
2668 T(2)=F(9,8)*T(1)
2670 R0=EXP(-(F(1,2)*T(1)))
2672 R5=EXP(-(F(1,1)*T(1)))
2674 Y1=(T(2)-F(7,2))*3/F(7,2)
2676 GØSUB 4000
2678 R0=R0*Y9
2680 Y1=(T(2)-F(7,1))*3/F(7,1)
2682 GØSUB 4000
2684 R5=R5*Y9
2686 Y1=(T(1)-F(2,2))*3/F(2,2)
2688 GØSUB 4000
2690 R0=R0*Y9
2692 Y1=(T(1)-F(2,1))*3/F(2,1)
2694 GØSUB 4000
2696 R5=R5*Y9
2698 GØSUB 3000
2700 PRINT USING 2,R0,R5,A0,B0
2702 IF F(9,9)=2 THEN 2654
2704 GØTØ 2660
2710 PRINT "MISSIØN TIME=?(0 TØ END)"
2712 INPUT T(4)
2714 IF T(4)<=0 THEN 200
2716 R0=EXP(-(F(4,2)*T(4)))
2718 R5=EXP(-(F(4,1)*T(4)))
2720 Y1=(T(4)-F(7,1))/(.15*F(7,1))
2722 GØSUB 4000
2724 R0=R0*(1-(1-Y9)*F(9,2))
2726 R5=R5*(1-(1-Y9)*F(9,1))
2728 IF B9=0 THEN 2742
2730 IF B9=2 THEN 2738
2732 R0=R0↑.2*EXP(-(F(2,2)*T(4)))
2734 R5=R5↑.2*EXP(-(F(2,1)*T(4)))
2736 GØTØ 2742
2738 R0=R0↑.4
2740 R5=R5↑.4
2742 GØSUB 3000
2744 PRINT USING 2,R0,R5,A0,B0
2746 GØTØ 2710
2750 PRINT "MISSIØN TIME TØ FIRING=?(YRS;0=END)"
2752 INPUT T(7)
2754 IF T(7)<=0 THEN 200
2756 Y1=(LØG(T(7))-LØG(F(7,2)))/.3991
2758 GØSUB 4000
2760 R0=Y9
2762 Y1=(LØG(T(7))-LØG(F(7,1)))/.3991
2764 GØSUB 4000
```

```
2766 R5=Y9
2768 GØSUB 3000
2770 PRINT USING 2,R0,R5,A0,B0
2772 PRINT "MISS. TIME=?"
2774 GØTØ 2752
2810 PRINT "ØP.PULSES=?(0=END)"
2812 INPUT T(2)
2813 IF T(2)<=0 THEN 200
2814 Y1=(T(2)-F(7,2))/(B7*F(7,2))
2816 GØSUB 4000
2818 R0=Y9
2820 Y1=(T(2)-F(7,1))/(B7*F(7,1))
2822 GØSUB 4000
2824 R5=Y9
2826 R0=R0*EXP(-(F(2,2)*T(2)))
2828 R5=R5*EXP(-(F(2,1)*T(2)))
2830 GØSUB 3000
2832 PRINT USING 2,R0,R5,A0,B0
2834 GØTØ 2810
2860 PRINT "MISSIØN TIME,ØP. TIME (TMISS=0=END)"
2862 INPUT T(4),T(1)
2864 IF T(4)<=0 THEN 200
2866 R0=EXP(F(1,2)*(T(1)-T(4)))
2868 R5=EXP(F(1,1)*(T(1)-T(4)))
2870 GØSUB 3000
2872 PRINT USING 2,R0,R5,A0,B0
2874 PRINT "MISS.TIME,ØP.TIME"
2876 GØTØ 2862
3000 IF (LØG(R0)/LØG(R5))<=1 THEN 3004
3001 S0=LØG(LØG(R0)/LØG(R5))/1.64485
3002 IF S0<.89146 THEN 3100
3003 GØTØ 3010
3004 IF R0>R5 THEN 3007
3005 PRINT "R0=R5, DISREGARD ALPHA,BETA"
3006 GØTØ 3210
3007 PRINT "PRØGRAM ERRØR ØR TAIL REVERSAL:R0>R5"
3008 PRINT "TRY VALUE CLØSER TØ MEAN LIFE"
3009 GØTØ 3210
3010 B0=.646/(LØG(S0)+.646)-1.21634
3012 IF B0<-.91 THEN 3068
3014 IF B0<-.2 THEN 3020
3016 M0=.45*(-B0)
3018 GØTØ 3090
3020 IF B0<-.3 THEN 3030
3022 M0=.09-.5*(B0+.2)
3024 GØTØ 3090
3030 IF B0<-.4 THEN 3040
3032 M0=.14-.575*(B0+.3)
3034 GØTØ 3090
```

```
3040 IF B0<-.5 THEN 3050
3042 M0=.1975-.675*(B0+.4)
3044 GØTØ 3090
3050 IF B0<-.6 THEN 3060
3052 M0=.265-.7*(B0+.5)
3054 GØTØ 3090
3060 IF B0<-.7 THEN 3070
3062 M0=.335-.9*(B0+.6)
3064 GØTØ 3090
3068 PRINT "ALPHA APPRØX. QUESTIØNABLE"
3070M0=.425-1.05*(B0+.7)
3074 GØTØ 3090
3090 A0= LØG(1-.5↑(1/(B0+1)))/LØG(R5)
3092 A0=(A0-1)/(M0+1)
3094 GØTØ 3210
3100 Z0=(S0/.8899)↑(-1/.4682)
3101 IF Z0<1 THEN 3104
3102 D=.1*Z0
3103 GØTØ 3105
3104 D=.1
3105 Z1=Z0
3106 IF Z1<=D THEN 3102
3110 GØSUB 3300
3112 IF ABS(S3-S0)<=.00005 THEN 3200
3114 S2=S3
3116 Z1=Z0-D
3118 IF .8899*(Z1↑(-.4682))*(1/(2*Z1-1))↑(.0273/(Z1↑.5))>S0
                                                        THEN 3130
3120 GØSUB 3300
3122 IF ABS(S3-S0)<=.00005 THEN 3200
3124 IF S3>S0 THEN 3130
3126 Z0=Z1
3128 GØTØ 3116
3130 D=.1*D
3132 IF D<.0002 THEN 3200
3134 GØTØ 3116
3200 A0=Z9
3202 B0=Z1
3210 RETURN
3300 Z9=(2*R5*(Z1-.6)+.6)/(2*(1-R5))
3302 S3=(Z9+Z1-1)/((2*Z1-1)*(Z9-Z1+1))
3303 IF S3<=0 THEN 3320
3304 S3=S3↑(.0273/(Z1↑.5))
3306 S3=S3*.8899*(Z1↑(-.4682))
3310 RETURN
3320 PRINT "ØUT ØF RANGE; TRY SMALLER ØR LARGER TIME/PULSES"
3322 GØTØ 99999
4000 Y8=SGN(Y1)
4001 IF ABS(Y1)<5 THEN 4010
```

```
4002 Y9=.5-Y8*.49999999
4003 PRINT "I,APPRØX. NØRM PRØB."
4004 PRINT Y1,Y9
4005 GØTØ 4050
4010 Y9=1
4012 I=1
4014 Y7=1
4020 Y6=((-1)↑I)*(Y1↑(2*I))/((2↑I)*Y7*(2*I+1))
4022 Y9=Y9+Y6
4024 IF ABS(Y6)<.000001 THEN 4040
4026 I=I+1
4028 IF I>40 THEN 4040
4029 Y7=Y7*I
4030 GØTØ 4020
4040 Y9=.5-Y8*Y9*ABS(Y1)*((2/3.141592)↑.5)/2
4050 RETURN
99998 PRINT "NØ SUCH CØMPØNENT"
99999 END
```

Table 9

Alpha Numeric Component Code Listing

	COMPONENT	COMP 1 EQUATION
1.	Gimbal Thrust Vectoring	
	1.1 Lower Support	LS
	1.2 Upper Support	US
	1.3 Linear Actuator	LA
	1.4 Motor and Gearing	MG
2.	Bladder, Mercury	BB
3.	Fill Valve, Pressurized System	FV1
5.	Pressurized Tank	
	5.1 Whole Tank	TT
	5.2 Propellant Reservoir	PR
	5.3 Pressurant Tank	PT
6.	Vaporizer	
	6.1 Vaporizer Clogged	VC
	6.2 Vaporizer Leakage	VL
7.	PCC Switch	
	7.1 Fails Active	SA
	7.2 Fails Passive	SP
8.	Propellant Feed Lines	FL
9.	Cathode, hollow	HC
10.	Isolator	II
11.	Neutralizer Isolator	NI
12.	Neutralizer Vaporizer	NV
13.	Neutralizer Cathode	NC
14.	Discharge Chamber, Kaufman	DC
15.	Vaporizer Heater	VH
16.	PCC Failure, Mercury Ion	MPC

	COMPONENT	COMP 1 EQUATION
17.	Line, Tank or Valve Heater	HLTV
18.	Unpressurized Surface Tension Tank Cesium	USTT
19.	Discharge Chamber, MESC type, including TVC	MESC
20.	Neutralizer Probe Cesium Ion System	NP
21.	PCC, Cesium Ion, MESC Type	CPC
22.	Vapor Valve Cesium	
	22.1 Fails Part Open	VVP
	22.2 Fails Open	VVO
	22.3 Fails Closed	VVC
23.	Trapped Gas in Cesium Tank	TG
24.	Propellant (Cesium) Tank Leakage	PCTL
25.	Vapor Valve Heater, (also Vaporizer Heater	VVH
26.	Fins Unwetted	FU
27.	Propellant Storage Bellows (Colloid)	PSB
28.	Fill Valve, Colloid	FV2
29.	Filter, Colloid	
	29.1 Clogging	FCC
	29.2 Leaking	FCL

	COMPONENT	COMP 1 EQUATION
30.	Propellant Flow Control Valve, (Ball Valve) Colloid (Ball Valve)	
	30.1 Leak to Space	BVL
	30.2 Ball Valve Closed	BVC
	30.3 Ball Valve Fails Open	BVO
31.	Zeolite Cannister Failure	ZC
32.	System Manifold, Colloid	SM
33.	Control Bellows, Colloid	CB
34.	Colloid PCC	CPCC
35.	Colloid Thruster Module	CTM
36.	Colloid Thruster Frame	CTF
37.	Electrofluidic Isolation Valve	
	37.1 Electrical Failure	EIV
	37.2 Fluid Failure	FIV
38.	Filament Neutralizer Colloid	FNC
39.	Main Capacitor, Pulsed Plasma	MCP1
40.	Negator Spring, Pulsed Plasma	NS
41.	Main Electrode Failure, Pulsed Plasma	ME
42.	Control Logic, Pulsed Plasma	CL
43.	Low Voltage Converter, Pulsed Plasma	LVC
44.	High Voltage Converter, Pulsed Plasma	HVC
45.	System Power Converter, Pulsed Plasma	SPC

COMPONENT	COMP 1 EQUATION
46. Sense Circuit Pulsed Plasma	SC
47. Initiator Plug Pulsed Plasma	IP
48 Pulse Buffer Failure	PB
49. Isolation Valve Solenoid Type, Normally Closed or Latch Valve	
49.1 Fail Open	ILVO
49.2 Fail Closed	ILVC
49.3 Fail Partial	ILVP
49.4 Fail Leak to Space	ILVL
50. Regulator	
50.1 Fails or Biased Low	RBL
50.2 Fails High or Oscillatory	RHO
51. Check Valve	
51.1 Fails Open	CVO
51.2 Fails Closed	CVC
51.3 Fail Partially Open/Closed	CVP
52. Engine Valve	
52.1 Fail Open	EVO
52.2 Fail Closed	EVC
52.3 Fail Partial	EVP
52.4 Fail Leak to Space	EVLS
53. Bladder/Diaphragm	
53.1 Elastomerics	
53.1.1 Fuel	
53.1.1.1 $0 \leq$ Mission Time ≤ 2.5 yrs	BEF1
53.1.1.2 Mission time > 2.5 yrs	BEF2
53.1.2 Oxidizer	
53.1.3.1 $0 \leq$ Mission Time ≤ 1.5 yrs	BEO1
53.1.2.2 Mission > 1.5 yrs	BEO2

COMPONENT	COMP 1 EQUATION
53.2 Metallics	
53.2.1 0≤Mission Time≤5 yrs.	BM1
53.2.2 5 yrs≤Mission Time<10+ yrs.	BM2
54. Filter, Thermochemical System	
54.1 Leaking	FTL
54.2 Clogging	FTC
55. Heaters, External Thruster	HET
56. Injector (including Trim Orifice)	
56.1 Plugging	IMP
56.2 Fracture	IMF
56.3 Injector Seal Leak	ISL
56.4 Injector Braze Failure	IBF
57. Catalyst Bed	
57.1 Pulse Mode	CBP
57.2 Steady State	CBS
57.3 Dormant	CBD
58. Thrust Chamber, Monoprop	TCM
59. Thrust Chamber Bipropellant	TCB
60. Relief Valve	RV
61. Heater, Thruster Internal	HTI
62. Thruster Screens and Retainer Electrothermal	TSR
63. Explosive Isolation Valve	EIV2
64. Burst Diaphragm	BD
65. Surface Tension Fins Unwetting	STFU

BETSB1 Program Listing

```
1: SUBSYSTEM EVALUATION
2 PRINT "RUN IN DOUBLE PRECISION"
4 S8=0
5 S9=0
10 PRINT "TYPE OF INPUT(1=PARAM,2=MEAN&VAR)"
12 INPUT S1
14 PRINT "HOW MANY COMPONENTS?"
16 INPUT N
18 PRINT "INDEPENDENT=1,IDENTICAL=2"
20 INPUT S2
22 PRINT "SERIES=1,REDUNDANT=2"
24 INPUT S3
26 PRINT "VALUES"
28 IF S1=2 GOTO 44
30 IF S2=2 GOTO 40
32 FOR I=1 TO N
34 INPUT A(I),B(I)
36 NEXT I
38 GOTO 70
40 INPUT A(1),B(1)
42 GOTO 70
44 IF S2=2 GOTO 64
46 FOR I=1 TO N
48 INPUT E1,E2
50 GOSUB 300
60 NEXT I
62 GOTO 70
64 I=1
66 INPUT E1,E2
68 GOSUB 300
70 IF S1=2 GOTO 76
71 IF S2=2 GOTO 90
72 IF N=1 GOTO 90
74:##       ##.###    ##.###
76 PRINT
78 PRINT "COMP.  ALPHA    BETA"
80 PRINT
81 FOR I=1 TO N
82 IF I=1 GOTO 84
83 IF S2=2 GOTO 87
84 PRINT USING 74,I,A(I),B(I)
85 IF A(I)<100 GOTO 87
```

```
86 PRINT A(I)
87 NEXT I
88 PRINT
90 IF S2=2 GOTO 92
91 IF S3=1 GOTO 100
92 IF S2=1 GOTO 94
93 IF S3=1 GOTO 104
94 IF S2=2 GOTO 96
95 IF S3=2 GOTO 108
96 GOSUB 400
98 GOTO 110
100 GOSUB 500
102 GOTO 110
104 GOSUB 600
106 GOTO 110
108 GOSUB 700
110 I=N+1
112 GOSUB 302
114:###.##  ##.###  .########  .########  .########
116 PRINT "SUBSYSTEM"
118 PRINT "ALPHA   BETA        E(P)       E(P*P)     V(P)"
120 PRINT
122 PRINT USING 114,A(N+1),B(N+1),E1,E2,E2-E1↑2
123 IF A(N+1)<1000 GOTO 125
124 PRINT A(N+1)
125 PRINT
126 PRINT
130 IF S9=0 GOTO 150
132 E1=(A(N+1)+1)/(A(N+1)+B(N+1)+2)
134 A(N+1)=(2*E1-1)/(1-E1)
136 E2=E1*(A(N+1)+2)/(A(N+1)+3)
138 B(N+1)=0
140 S9=0
142 PRINT
144 PRINT "IF NEGATIVE SUBSYSTEM BETA NOT ALLOWED"
146 GOTO 116
150 IF S8=0 GOTO 990
152 FOR I=1 TO N
154 IF B(I)>=0 GOTO 164
156 E1=(A(I)+1)/(A(I)+B(I)+2)
158 A(I)=(2*E1-1)/(1-E1)
162 B(I)=0
164 NEXT I
166 PRINT "IF NEGATIVE BETA NOT ALLOWED"
168 PRINT "NEW COMPONENT VALUES"
170 S8=0
172 PRINT
174 PRINT "COMP.  ALPHA  BETA"
176 PRINT
178 FOR I=1 TO N
```

```
180 PRINT USING 74,I,A(I),B(I)
182 IF A(I)<100 GOTO 186
184 PRINT A(I)
186 NEXT I
188 PRINT
190 GOTO 90
300 E2=E2+E1↑2
302 C=E2/E1
304 B(I)=(1-C)*(E1-1)/(E1-C)-1
305 IF B1<=(-1) GOTO 330
306 A(I)=(B(I)+1)*E1/(1-E1)-1
308 IF B(I)>=0 GOTO 314
309  IF I>N GOTO 312
310 S8=1
311 GOTO 314
312 S9=1
314 RETURN
330:BETA(###) ILLEGAL
332 PRINT USING 330,I
400 G1=1
402 G2=1
404 FOR I=1 TO N
406 G1=G1*(B(I)+I)/(A(I)+B(I)+I+1)
408 G2=G2*(B(I)+2*I-1)/(A(I)+B(I)+2*I)*(B(I)+2*I)/(A(I)+
                                                        B(I)+2*I+1)
410 NEXT I
412 E1=1-G1
414 E2=1-2*G1+G2
420 RETURN
500 G1=1
502 G2=1
504 FOR I=1 TO N
506 G1=G1*(A(I)+1)/(A(I)+B(I)+2)
508 G2=G2*(A(I)+2)/(A(I)+B(I)+3)
510 NEXT I
512 E1=G1
514 E2=G1*G2
520 RETURN
600 G1=1
602 G2=1
604 FOR I=1 TO N
606 G1=G1*(A(I)+I)/(A(I)+B(I)+I+1)
608 G2=G2*(A(I)+2*I)/(A(I)+B(I)+2*I)*(A(I)+2*I-1)/(A(I)+
                                                        B(I)+2*I+1)
610 NEXT I
612 E1=G1
614 E2=G2
```

```
620 RETURN
700 G1=1
702 G2=1
704 FOR I=1 TO N
706 G1=G1*(B(I)+1)/(A(I)+B(I)+2)
708 G2=G2*(B(I)+2)/(A(I)+B(I)+3)
710 NEXT I
712 E1=1-G1
714 E2=1-2*G1+G1*G2
720 RETURN
990 END
```

```
100 PRINT "M-OF-N,INDEPENDENT"
110 PRINT "RUN IN DOUBLE PRECISION"
120 S8=0
130 S9=0
140 DIM A(21),B(21),U(21),Z(21)
142 DIM H(150,21)
150 PRINT "TYPE OF INPUT(1=PARAM,2=MEAN&VAR)"
160 INPUT S1
170 PRINT "HOW MANY COMPONENTS?"
180 INPUT N
190 PRINT "HOW MANY REQ'D?"
200 INPUT S3
202 PRINT "SAME PARAMS?(1=YES,0=NO)"
204 INPUT S4
210 IF S4=1 THEN 4000
222 GOSUB 1610
224 IF L1<150 THEN 230
226 PRINT "RESET DIM AT 142"
227:USING ### TO REPLACE 150
228 PRINT USING 227,L1
229 GOTO 9999
230 PRINT "VALUES"
240 IF S1=2 GOTO 330
260 FOR I=1 TO N
270 INPUT A(I),B(I)
290 NEXT I
312 PRINT
320 GOTO 470
330 PRINT "COMP.  ALPHA    BETA"
332 FOR I=1 TO N
334 INPUT E1,E2
350 GOSUB 1200
356 PRINT USING 390,I,A(I),B(I)
358 NEXT I
360 PRINT
390:##     ##.####  ##.####
470 E1=0
480 E2=0
490 GOSUB 1820
500 GOTO 900
510 I=N+1
520 GOSUB 1200
```

```
530:##.#### ##.#### .######### .########## .#########
540 PRINT "SUBSYSTEM"
550 PRINT "ALPHA   BETA      E(P)      E(P*P)    V(P)"
560 PRINT
570 PRINT USING 530,A(N+1),B(N+1),E1,E2,E2-E1↑2
580 IF A(N+1)<100 GOTO 600
590 PRINT A(N+1)
600 PRINT
610 PRINT
612 IF B(N+1)>=0 THEN 9999
620 IF S9=0 GOTO 710
630 E1=(A(N+1)+1)/(A(N+1)+- N+1)+2)
640 A(N+1)=(2*E1-1)/(1-E1)
650 E2=E1*(A(N+1)+2)/(A(N+1)+3)
660 B(N+1)=0
670 S9=0
680 PRINT
690 PRINT "IF NEGATIVE SUBSYSTEM BETA NOT ALLOWED"
700 GOTO 540
710 IF S8=0 THEN 9999
720 FOR I=1 TO N
730 IF B(I)>=0 GOTO 770
740 E1=(A(I)+1)/(A(I)+B(I)+2)
750 A(I)=(2*E1-1)/(1-E1)
760 B(I)=0
770 NEXT I
772 PRINT
780 PRINT "IF NEGATIVE BETA NOT ALLOWED"
790 PRINT "NEW COMPONENT VALUES"
800 S8=0
810 PRINT
820 PRINT "COMP.  ALPHA  BETA"
830 PRINT
840 FOR I=1 TO N
850 PRINT USING 390,A(I),B(I)
860 IF A(I)<100 THEN 880
870 PRINT A(I)
878 NEXT I
880 PRINT
890 GOTO 470
900 FOR I=1 TO L1
910 D3=1
920 D4=1
930 FOR K2=1 TO N
940 IF H(I,K2)<.5 THEN 980
950 D3=D3*(A(K2)+1)
960 D4=D4*(A(K2)+1)*(A(K2)+2)
970 GOTO 992
980 D3=D3*(B(K2)+1)
990 D4=D4*(B(K2)+1)*(B(K2)+2)
```

```
992 D3=D3/(A(K2)+B(K2)+2)
994 D4=D4/((A(K2)+B(K2)+2)*(A(K2)+B(K2)+3))
1000 NEXT K2
1010 E1=E1+D3
1020 E2=E2+D4-D3↑2
1030 NEXT I
1050 FOR I=1 TO L1-.99
1052 FOR J=I+1 TO L1+.01
1054 D2=1
1056 D3=1
1058 D4=1
1060 FOR K2=1 TO N
1070 F9=H(I,K2)+H(J,K2)
1071 GOSUB 1400
1072 NEXT K2
1080 E2=E2+2*(D2-D3*D4)
1082 NEXT J
1090 NEXT I
1100 GOTO 510
1200 E2=E2+E1↑2
1210 C=E2/E1
1220 B(I)=(1-C)*(E1-1)/(E1-C)-1
1230 IF B(I)<=(-1) GOTO 1310
1240 A(I)=(B(I)+1)*E1/(1-E1)-1
1250 IF B(I)>=0 GOTO 1300
1260 IF I>N GOTO 1290
1270 S8=1
1280 GOTO 1300
1290 S9=1
1300 RETURN
1310:BETA(###) ILLEGAL
1320 PRINT USING 1310,I
1322 GOTO 9999
1400 IF F9<.5 THEN 1450
1410 D2=D2*(A(K2)+1)
1420 IF F9<1.5 THEN 1450
1430 D2=D2*(A(K2)+2)
1440 GOTO 1480
1450 D2=D2*(B(K2)+1)
1460 IF F9>.5 THEN 1480
1470 D2=D2*(B(K2)+2)
1480 D2=D2/((A(K2)+B(K2)+2)*(A(K2)+B(K2)+3))
1490 IF H(I,K2)<.5 THEN 1520
1500 D3=D3*(A(K2)+1)/(A(K2)+B(K2)+2)
1510 GOTO 1530
1520 D3=D3*(B(K2)+1)/(A(K2)+B(K2)+2)
1530 IF H(J,K2)<.5 THEN 1560
1540 D4=D4*(A(K2)+1)/(A(K2)+B(K2)+2)
1550 GOTO 1570
1560 D4=D4*(B(K2)+1)/(A(K2)+B(K2)+2)
```

```
1570 RETURN
1610 D1=1
1611 L1=1
1612 IF N-S3<.99 THEN 1740
1613 Z(1)=1
1614 L1=N+1
1615 Z(2)=N+1
1616 IF N-S3<1.99 THEN 1740
1618 FØR X=2 TØ N-S3+.01
1620 D1=1
1640 FØR D2=X+1 TØ N+.01
1650 D1=D1*D2
1660 NEXT D2
1662 IF N-X<2 THEN 1720
1670 FØR D2=2 TØ N-X+.01
1680 D1=D1/D2
1690 NEXT D2
1720 L1=L1+D1
1726 Z(X+1)=Z(X)+D1
1730 NEXT X
1740 RETURN
1820 FØR I=2↑N-1 TØ 0.99 STEP -1
1822 S7=I
1824 FØR J=N TØ 1.99 STEP -1
1825 U(J)=0
1826 IF S7<2↑(J-1)-.1 THEN 1832
1828 U(J)=1
1830 S7=S7-2↑(J-1)
1832 NEXT J
1833 U(1)=0
1834 IF S7<.99 THEN 1840
1836 U(1)=1
1840 K1=0
1842 FØR J=1 TØ N
1844 K1=K1+U(J)
1846 NEXT J
1847 IF K1<S3 THEN 1858
1848 IF N-K1<1 THEN 1858
1850 Z(N-K1)=Z(N-K1)+1
1852 FØR J=1 TØ N
1854 H(Z(N-K1),J)=U(J)
1856 NEXT J
1858 NEXT I
1860 FØR J=1 TØ N
1862 H(1,J)=1
1864 NEXT J
1880 RETURN
1900 H(K1,K2)=0
1910 IF K2>K1+.01 THEN2020
```

```
1912 IF K1<.99 THEN2020
1920 H(K1,K2)=1
1930 IF ABS(K1-K2 )<.01 THEN2020
1940 IF K1<2.99 THEN 2020
1950 FØR K3=(K1-K2+1) TØ K1-.99
1960 H(K1,K2)=H(K1,K2)*K3
1970 NEXT K3
1980 IF K2<2.99 THEN 2020
1990 FØR K3=2 TØ K2-.99
2000 H(K1,K2)=H(K1,K2)/K3
2010 NEXT K3
2020 RETURN
3000 E1=((A(1)+1)/(A(1)+B(1)+2))↑N
3010 E2=((A(1)+1)*(A(1)+2)/(A(1)+B(1)+2)/(A(1)+B(1)+3))↑N
3020 E2=E2-E1↑2
3030 IF L1<1.99 THEN 510
3040 FØR X=1 TØ N-S3+.01
3050 D3=((A(1)+1)↑(N-X)*(B(1)+1)↑X)/(A(1)+B(1)+2)↑N
3060 D4=((A(1)+1)*(A(1)+2))↑(N-X)
3070 D4=D4*((B(1)+1)*(B(1)+2))↑X
3080 D4=D4/((A(1)+B(1)+2)*(A(1)+B(1)+3))↑N
3090 D4=D4-D3↑2
3100 E1=E1+D3*(Z(X+1)-Z(X))
3110 E2=E2+D4*(Z(X+1)-Z(X))
3120 NEXT X
3130 FØR I=0 TØ N-S3-.99
3140 K1=N+1
3150 K2=I+1
3160 GØSUB 1900
3170 F1=H(K1,K2)
3200 FØR J=I+1 TØ N-S3+.01
3202 K1=N+1
3210 K2=J+1
3220 GØSUB 1900
3230 F2=H(K1,K2)
3240 D4=(A(1)+1)↑(N-J)*(B(1)+1)↑J
3250 D4=D4/(A(1)+B(1)+2)↑(2*N)
3260 D4=D4*(A(1)+1)↑(N-I)*(B(1)+1)↑I
3270 E2=E2-2*F1*F2*D4
3280 FØR F3=0 TØ I+.01
3290 K1=I+1
3300 K2=F3+1
3310 GØSUB 1900
3320 F4=H(K1,K2)*F1*F2
3330 IF F3<.99 THEN 3370
3340 FØR K1=1 TØ F3+.01
3350 F4=F4*(J-K1+1)
3360 NEXT K1
3370 IF I-F3<.99 THEN 3410
```

```
3380 FØR K1=1 TØ (I-F3+.01)
3390 F4=F4*(N-J-K1+1)
3400 NEXT K1
3410 IF I<.99 THEN 3450
3420 FØR K1=1 TØ I+.01
3430 F4=F4/(N-K1+1)
3440 NEXT K1
3450 D4=1
3460 IF F3<.99 THEN 3480
3470 D4=D4*((B(1)+1)*(B(1)+2))↑F3
3480 IF (I+J-2*F3)<.99 THEN 3500
3490 D4=D4*((A(1)+1)*(B(1)+1))↑(I+J-2*F3)
3500 IF (N-I-J+F3)<.99 THEN 3520
3510 D4=D4*((A(1)+1)*(A(1)+2))↑(N-I-J+F3)
3520 D4=D4/((A(1)+B(1)+2)*(A(1)+B(1)+3))↑N
3530 E2=E2+2*F4*D4
3540 NEXT F3
3550 NEXT J
3560 NEXT I
3570 FØR I=1 TØ N-S3+.01
3580 K1=N+1
3590 K2=I+1
3600 GØSUB 1900
3610 F5=H(K1,K2)
3615 FØR F3=0 TØ I-.99
3620 K1=I+1
3630 K2=F3+1
3640 GØSUB 1900
3650 F4=F5*H(K1,K2)
3660 K1=N-I+1
3670 K2=I-F3+1
3672 IF K2>K1 THEN 3800
3675 GØSUB 1900
3680 F4=F4*H(K1,K2)/2
3690 D3=(A(1)+1)↑(N-I)*(B(1)+1)↑I
3700 D3=(D3/(A(1)+B(1)+2)↑N)↑2
3710 E2=E2-2*F4*D3
3720 D4=((B(1)+1)*(B(1)+2))↑F3
3730 D4=D4*((A(1)+1)*(B(1)+1))↑(2*(I-F3))
3740 D4=D4*((A(1)+1)*(A(1)+2))↑(N-2*I+F3)
3750 D4=D4/((A(1)+B(1)+2)*(A(1)+B(1)+3))↑N
3760 E2=E2+2*F4*D4
3800 NEXT F3
3810 NEXT I
3820 GØTØ 510
4000 PRINT "VALUES?"
4002 IF S1=2 THEN 4030
4010 INPUT A(1),B(1)
4020 GØTØ 4110
```

```
4030 INPUT E1,E2
4040 I=1
4050 GØSUB 1200
4060 PRINT "ALPHA    BETA"
4070:###.####  ###.####
4080 PRINT USING 4070,A(I),B(I)
4090 IF A(I)<1000 THEN 4110
4100 PRINT A(I)
4110 GØSUB 1610
4120 GØTØ 3000
9999 END
READY.
```

BETSB 3 Program Listing

```
1 PRINT "M-ØF-N IDENTICAL"
2 PRINT "RUN IN DØUBLE PRECISIØN"
4 S8=0
5 S9=0
7 DIM A(21),B(21)
8 DIM H(200,10)
10 PRINT "TYPE ØF INPUT(1=PARAM,2=MEAN&VAR)"
12 INPUT S1
14 PRINT "HØW MANY CØMPØNENTS?"
16 INPUT N
22 PRINT "HØW MANY REQ'D?"
24 INPUT S3
26 PRINT "VALUES"
28 IF S1=2 THEN 64
32 INPUT A(1),B(1)
38 GØTØ 76
64 I=1
66 INPUT E1,E2
68 GØSUB 300
70 PRINT "ALPHA   BETA"
72 PRINT USING 74,A(1),B(1)
74:###.####  ###.####
76 PRINT
100 E1=0
102 E2=0
104 GØTØ 204
110 I=N+1
112 GØSUB 300
114:###.#### ##.#### .#########  .#########  .#########
116 PRINT "SUBSYSTEM"
118 PRINT "ALPHA   BETA      E(P)      E(P*P)    V(P)"
120 PRINT
122 PRINT USING 114,A(N+1),B(N+1),E1,E2,E2-E1↑2
123 IF A(N+1)<1000 GØTØ 125
124 PRINT A(N+1)
125  PRINT
126 PRINT
130 IF S9=0 THEN 150
132 E1=(A(N+1)+1)/(A(N+1)+B(N+1)+2)
134 A(N+1)=(2*E1-1)/(1-E1)
136 E2=E1*(A(N+1)+2)/(A(N+1)+3)
138 B(N+1)=0
140 S9=0
```

```
142 PRINT
144 PRINT "IF NEGATIVE SUBSYSTEM BETA NØT ALLØWED"
146 GØTØ 116
150 IF S8=0 THEN 9999
152 FØR I=1 TØ N
154 IF B(I)>=0 GØTØ 164
156 E1=(A(I)+1)/(A(I)+B(I)+2)
158 A(I)=(2*E1-1)/(1-E1)
162 B(I)=0
164 NEXT I
166 PRINT "IF NEGATIVE BETA NØT ALLØWED"
168 PRINT "NEW CØMPØNENT VALUES"
170 S8=0
172 PRINT
174 PRINT "CØMP.  ALPHA  BETA"
176 PRINT
178 I=1
180 PRINT USING 74,I,A(I),B(I)
182 IF A(I)<1000 THEN 188
184 PRINT A(I)
188 PRINT
190 GØTØ 100
193:9
198:99
204 FØR I=0 TØ N-S3+.01
206 K1=N+1
208 K2=I+1
210 GØSUB 1900
212 F4=H(K1,K2)
214 GØSUB 1000
216 E1=E1+F4*D1
218 GØSUB 1200
220 E2=E2+F4*(D2-D1↑2)
222 IF I<.99 THEN 236
224 K1=F4+1
226 K2=3
230 GØSUB 1900
232 F4=H(K1,K2)
234 E2=E2+2*F4*(D2-D1↑2)
236 NEXT I
238 FØR I1=0 TØ N-S3-.99
240 K1=N+1
242 K2=I1+1
244 GØSUB 1900
246 F5=H(K1,K2)
248 I=I1
250 GØSUB 1000
252 D3=D1
254 FØR I2=I1+1 TØ N-S3+.01
```

```
256 K1=N+1
258 K2=I2+1
260 GØSUB 1900
262 F4=H(K1,K2)
264 I=I2
266 GØSUB 1000
268 D4=D3*D1
270 D2=D1
272 FØR K1=1 TØ N-I1+.01
274 D2=D2*(A(1)+N-I2+K1)
276 NEXT K1
278 IF I1<.99 THEN 286
280 FØR K1=1 TØ I1+.01
282 D2=D2*(B(1)+I2+K1)
284 NEXT K1
286 FØR K1=1 TØ N
288 D2=D2/(A(1)+B(1)+N+K1+1)
290 NEXT K1
292 E2=E2+2*F4*F5*(D2-D4)
294 NEXT I2
296 NEXT I1
298 GØTØ 110
300 E2=E2+E1↑2
302 C=E2/E1
304 B(I)=(1-C)*(E1-1)/(E1-C)-1
305 IF B(I)<=(-1) GØTØ 330
306 A(I)=(B(I)+1)*E1/(1-E1)-1
308 IF B(I)>=0 GØTØ 314
309 IF I>N GØTØ 312
310 S8=1
311 GØTØ 314
312 S9=1
314 RETURN
330:BETA(###) ILLEGAL
332 PRINT USING 330,I
334 GØTØ 9999
1000 D1=1
1010 IF I<.99 THEN 1050
1020 FØR K1=1 TØ I+.01
1030 D1=D1*(B(1)+K1)
1040 NEXT K1
1050 FØR K1=1 TØ N-I+.01
1060 D1=D1*(A(1)+K1)
1070 NEXT K1
1080 FØR K1=1 TØ N
1090 D1=D1/(A(1)+B(1)+K1+1)
1100 NEXT K1
```

```
1110 RETURN
1200 D2=1
1210 IF I<.99 THEN 1250
1220 FØR K1=1 TØ I+.01
1230 D2=D2*(B(1)+2*K1)*(B(1)+2*K1-1)
1240 NEXT K1
1250 FØR K1=1 TØ N-I+.01
1260 D2=D2*(A(1)+2*K1)*(A(1)+2*K1-1)
1270 NEXT K1
1280 FØR K1=1 TØ 2*N+.01
1290 D2=D2/(A(1)+B(1)+K1+1)
1300 NEXT K1
1310 RETURN
1900 H(K1,K2)=0
1910 IF K2>K1 THEN 2020
1912 IF K1<.99 THEN 2020
1920 H(K1,K2)=1
1930 IF ABS(K1-K2)<.01 THEN 2020
1940 IF K1 <2.99 THEN 2020
1950 FØR K3=(K1-K2+1) TØ K1-.99
1960 H(K1,K2)=H(K1,K2)*K3
1970 NEXT K3
1980 IF K2<2.99 THEN 2020
1990 FØR K3=2 TØ K2-.99
2000 H(K1,K2)=H(K1,K2)/K3
2010 NEXT K3
2020 RETURN
9999 END
READY.
```

BETFTA Program Listing

```
1 PRINT "FØR EXPLANATIØN LIST 80000"
2 DIM M(20),G(20,100),D(20,100),C(20,100),T(20,100),U(20,100)
4 DIM A(20),B(20)
6 PRINT "HØW MANY LEVELS?"
8 INPUT L
12 PRINT "EVENTS? (LØWEST FIRST) (SINGLE ASSUMED AT TØP)"
13 FØR I=1 TØ L-.99
14 INPUT M(I)
15 NEXT I
16 M(L)=1
18 K2=1
20 PRINT "DESTINATIØN?"
22 FØR I=1 TØ L-.99
24 FØR J=1 TØ M(I)
25 C(I,J)=1
26 PRINT I;J;
28 INPUT D(I,J)
29 G(I+1,D(I,J))=-1
30 NEXT J
32 NEXT I
34 PRINT "CØNDITIØNALS?(0,0=SKIP)"
35 INPUT I,J
36 IF I=0 THEN 41
37 PRINT "PCØNDITIØNAL"
38 INPUT C(I,J)
39 PRINT "NEXT?"
40 GØTØ 35
41 PRINT "GATE TYPES"
42 FØR I=2 TØ L
43 FØR J=1 TØ M(I)
44 IF G(I,J)>-.5 THEN 48
45 PRINT I;J;
46 INPUT K3
47 G(I,J)=K3
48 NEXT J
49 NEXT I
50 FØR I=1 TØ L-.99
52 FØR J=1 TØ M(I)
54 IF G(I,J)>0 THEN 60
58 READ T(I,J),U(I,J)
60 NEXT J
62 NEXT I
```

```
64 PRINT
70 FØR I1=1 TØ L-.99
72 FØR J1=1 TØ M(I1)
74 IF N>0 THEN 78
76 K1=D(I1,J1)
78 N=N+1
80 A(N)=T(I1,J1)
82 B(N)=U(I1,J1)
84 IF C(I1,J1)=1 THEN 90
86 A(N)=(A(N)+B(N)+2)/C(I1,J1)-B(N)-2
90 IF J1>=M(I1) THEN 200
92 IF D(I1,J1+1)<>K1 THEN 200
94 NEXT J1
96 NEXT I1
100 PRINT
102 PRINT
106:SYSTEM (ITERATIØN ##)
108 PRINT USING 106,K2
110 PRINT "ALPHA   BETA   E(P)     E(P*P)    V(P)"
112 PRINT
114:##.#### ##.#### .######  .######  .########
116 E1=(T(L,1)+1)/(T(L,1)+U(L,1)+2)
118 E2=E1*(T(L,1)+2)/(T(L,1)+U(L,1)+3)
120 PRINT USING 114,T(L,1),U(L,1),E1,E2,E2-E1↑2
122 PRINT
124 PRINT
130 K2=K2+1
136 GØTØ 50
200 ØN G(I1+1,K1)+.1 GØTØ 500,700,600,400
202 T(I1+1,K1)=A(N+1)
204 U(I1+1,K1)=B(N+1)
205 PRINT I1+1;K1;A(N+1),B(N+1)
206 N=0
210 GØTØ 94
300 I=N+1
302 C=E2/E1
304 B(I)=(1-C)*(E1-1)/(E1-C)-1
305 IF B(I)<=(-1) THEN 330
306 A(I)=(B(I)+1)*E1/(1-E1)-1
314 GØTØ 202
330:BETA(#, ###) ILLEGAL
332 PRINT USING 330,I1+1,K1
334 GØTØ 99999
400 G1=1
402 G2=1
404 FØR I=1 TØ N
406 G1=G1*(B(1)+I)/(A(1)+B(1)+I+1)
408 G2=G2*(B(1)+2*I-1)/(A(1)+B(1)+2*I)*(B(1)+2*I)/(A(1)+
                                                  B(1)+2*I+1)
```

```
410 NEXT I
412 E1=1-G1
414 E2=1-2*G1+G2
420 GOTO 300
500 G1=1
502 G2=1
504 FOR I=1 TO N
506 G1=G1*(A(I)+1)/(A(I)+B(I)+2)
508 G2=G2*(A(I)+2)/(A(I)+B(I)+3)
510 NEXT I
512 E1=G1
514 E2=G1*G2
520 GOTO 300
600 G1=1
602 G2=1
604 FOR I=1 TO N
606 G1=G1*(A(1)+I)/(A(1)+B(1)+I+1)
608 G2=G2*(A(1)+2*I)/(A(1)+B(1)+2*I)*(A(1)+2*I-1)/(A(1)+
                                                   B(1)+2*I+1)
610 NEXT I
612 E1=G1
614 E2=G2
620 GOTO 300
700 G1=1
702 G2=1
704 FOR I=1 TO N
706 G1=G1*(B(I)+1)/(A(I)+B(I)+2)
708 G2=G2*(B(I)+2)/(A(I)+B(I)+3)
710 NEXT I
712 E1=1-G1
714 E2=1-2*G1+G1*G2
720 GOTO 300
80000 REM GATE TYPE  1  OR,INDEP; 2 AND,INDEP; 3 OR,ID;
                                               4 AND,ID
80002 REM GATE BELOW LEVEL I, JTH EVENT
80004 REM ALL GATES EXCEPT INHIBIT MUST BE SEPARATED BY EVENTS
80006 REM DESTINATION IS INDEX J OF I+1TH LEVEL EVENT
80008 REM PCONDITIONAL IS INHIBIT (FAIL) PROB. (DEFAULT=1)
80010 REM WRITE ALPHA,BETA IN DATA STATEMENTS 90000 UP
80012 REM STARTING WITH ALL LEVEL 1 (LOWEST), ETC
80014 REM IF MULTIPLE SETS PROVIDED, PROGRAM WILL ITERATE
80016 REM UNTIL DATA EXHAUSTED
80018 REM FOR TYPE 3&4 GATES, FIRST E VENT A,B ARE USED
99999 END
```

BETAL1 Program Listing

```
1 PRINT "RUN IN DOUBLE PRECISION"
2 DIM A(100),B(100),C(100),D(100),E(100),F(100),X(100)
3 PRINT "PERMIT NEGATIVE BETA?"
4 INPUT S9
6 F2=1
7 PRINT "TYPE OF INPUT?"
8 PRINT "1=PARAMETERS,2=MOMENTS (MEAN & VA)"
10 INPUT S1
12 PRINT "HOW MANY COMPONENTS?"
14 INPUT N
16 PRINT "VALUES? (THIRD VALUE IS COST OF FIRST TEST)"
17 FOR I=1 TO N
18 IF S1=1 THEN 22
19 INPUT E1,E2,C(I)
20 GOSUB 300
21 GOTO 24
22 INPUT A(I),B(I),C(I)
23 GOSUB 100
24 NEXT I
25 PRINT "DISPLAY COMPONENT VALUES?"
26 INPUT S2
27 IF S2=0 THEN 48
28 PRINT
30 PRINT "NO. ALPHA   BETA  E(P)    E(P*P)    V(P)     COST"
31 PRINT
32:### ####.## ##.## .###### .###### .######## ######.##
34 FOR I=1 TO N
36 GOSUB 100
38 PRINT USING 32,I,A(I),B(I),E1,E2,V,C(I)
39 IF A(I) <10000 THEN 41
40 PRINT A(I)
41 NEXT I
42 PRINT
44 PRINT
48 K1=0
50 GOSUB 200
52 PRINT "FIRST COMPONENT TESTED"
58 GOTO 400
100 E1=(A(I)+1)/(A(I)+B(I)+2)
102 E2=E1*(A(I)+2)/(A(I)+B(I)+3)
103 V=E2-(E1*E1)
104 IF I>1 THEN 107
```

```
105 F1=1
106 F2=1
107 F1=F1*E1
108 F2=F2*E2
120 RETURN
200 PRINT
202 PRINT
204 PRINT "FØR SYSTEM"
206 PRINT
208 C=F2/F1
210 B1=(1-C)*(F1-1)/(F1-C)-1
212 A1=(B1+1)*F1/(1-F1)-1
214 V=F2-(F1*F1)
216 PRINT
218 PRINT "E(R)      E(R*R)      V(R)"
220 PRINT
222:.######    .######    .########
224 PRINT USING 222,F1,F2,V
226 PRINT
228 PRINT
229 IF B1<0 THEN 360
230 R2=B1+1
231 IF ABS(B1+1-INT(B1+1))<.0000001 THEN 900
232 GØSUB 800
234 R4=-R
236 R2=A1+B1+2
237 IF (A1+1)>100 THEN 350
238 GØSUB 800
240 R4=R4+R
242 R2=A1+1
243 GØSUB 800
244 R4=EXP(R4-R)
245 U3=0
246 U4=0
247 U8=0
248 U5=0
249 U6=0
250 GØSUB 930
252 GØSUB 700
255 PRINT "CLØSURE"
256 PRINT U8*.00000001
257 PRINT "LØWER CØNF. BØUNDS"
258:80  .####  90  .####  95  .####
260 PRINT USING 258,U3,U4,U5
262 PRINT
264 PRINT
270 RETURN
300 E2=E2+E1*E1
301 C=E2/E1
```

```
302 B(I)=(1-C)*(Σ1-1)/(E1-C)-1
303 IF S9=1 THEN 305
304 IF B(I)<0 THEN 336
305 IF B(I)<(-1) THEN 330
306 A(I)=(B(I)+1)*E1/(1-E1)-1
308 IF I>1 THEN 314
310 F1=1
312 F2=1
314 F1=F1*E1
316 F2=F2*E2
320 RETURN
330 PRINT "ILLEGAL BETA"
332 GØTØ 990
334:B(###) CHANGED FRØM #.###
336 PRINT USING 334,I,B(I)
338 B(I)=0
340 A(I)=(2*E1-1)/(1-E1)
342 E2=E1*(A(I)+2)/(A(I)+3)
344 GØTØ 308
350 R1=(R2-.5)*LØG(R2)-(A1+.5)*LØG(A1+1)
352 R4=EXP(R4+R1-B1-1)
354 GØTØ 245
360 R2=B1+1
362 GØSUB 822
364 R=LØG(R3)-LØG(B1+1)
366 GØTØ 234
400 FØR I=1 TØ N
402 E1=(A(I)+1)/(A(I)+B(I)+2)
404 G1=(A(I)+1+E1)/(A(I)+B(I)+3)
406 E2=E1*(A(I)+2)/(A(I)+B(I)+3)
408 G2=G1*(A(I)+2+E1)/(A(I)+B(I)+4)
410 G3=F1*G1/E1
412 G4=F2*G2/E2
414 D(I)=F2-F1↑2-G4+G3↑2
416 X(I)=D(I)/C(I)
420 NEXT I
430 M=0
432 FØR I=1 TØ N
434 IF X(I)<M THEN 440
435 IF X(I)=M THEN 440
436 M=X(I)
438 S3=I
440 NEXT I
441 E(S3)=E(S3)+1
442 PRINT "NØ.    DELV      CØST      TØT CØST     NØ. TESTS"
443 F(S3)=F(S3)+C(S3)
444:### .######## ####.##  ######.##      ###
446 PRINT
447 K1=K1+C(S3)
```

```
448 PRINT USING 444,S3,X(S3),C(S3),K1,E(S3)
449 PRINT
450 I=S3
451 GØSUB 100
452 A(S3)=A(S3)+E1
453 B(S3)=B(S3)+1-E1
454 FØR I=1 TØ N
455 GØSUB 100
456 NEXT I
457 GØSUB 200
458 GØSUB 600
459 PRINT "CØNTINUE?"
460 INPUT K
461 IF K<.99 THEN 500
462 PRINT "CHANGE NEXT CØST?"
463 INPUT K
464 IF K<.99 THEN 487
465: NEW C(###)=?
466 PRINT USING 465,S3
468 INPUT C(S3)
487 PRINT
488 PRINT "NEW VALUES FØR LAST CØMPØNENT TESTED"
489 GØSUB 100
490 PRINT "NØ. ALPHA   BETA  E(P)    E(P*P)    V(P)     CØST"
491 PRINT USING 32,I,A(I),B(I),E1,E2,V,C(I)
492 PRINT
495 FØR I=1 TØ N
496 GØSUB 100
497 NEXT I
498 PRINT "NEXT CØMPØNENT TESTED"
499 GØTØ 400
500 PRINT "DISPLAY STATUS FØR ALL CØMPØNENTS?"
502 INPUT K4
504 IF K4<.99 THEN 990
506 PRINT
508 PRINT "NØ.  ALPHA   BETA   E(P)  TESTS   CØST"
510 PRINT
512:### ####.## ##.## .###### ### #######.##
513 FØR I=1 TØ N
514 GØSUB 100
515 PRINT USING 512,I,A(I),B(I),E1,E(I),F(I)
516 IF A(I)<10000 THEN 519
517 PRINT A(I)
519 NEXT I
520 PRINT
522 PRINT
530 GØTØ 990
600 PRINT
602 V8=F2-(F1*F1)
```

```
604 F5=1
606 F6=1
608 FØR I=1 TØ N
610 E1=(A(I)+1)/(A(I)+B(I)+2)
612 F3=(A(I)+E1+1)/(A(I)+B(I)+3)
614 F4=F3*(A(I)+E1+2)/(A(I)+B(I)+4)
616 F5=F5*F3
618 F6=F6*F4
620 NEXT I
622 V9=F6-(F5*F5)
624:E(DELVAR)=.########
626 PRINT USING 624,V8-V9
628 PRINT
630 PRINT
638 I=S3
640 RETURN
700 IF S4<.975 THEN 706
702 S5=.95
704 GØTØ 727
706 S6=.001*INT(1000*S4)+.025
708 FØR X=.999 TØ (S6-.0001) STEP -.001
710 GØSUB 840
712 NEXT X
714 S5=S6-.05
716 R4=R4/10
717 U6=.1*U6
718 FØR X=S6-.0001 TØ S5 STEP -.0001
720 GØSUB 840
722 NEXT X
724 R4=10*R4
725 IF S5<0 THEN 736
726 IF S5=0 THEN 736
727 U6=10*U6
728 FØR X=S5-.001 TØ 0 STEP -.001
730 GØSUB 840
732 NEXT X
734 GØTØ 740
736 PRINT "MØDE <=.025"
738 PRINT "INTEGRATIØN TRUNCATED"
740 RETURN
800 R1=0
804 IF R2<2 THEN 820
805 IF R2=2 THEN 820
806 R1=R1+LØG(R2-1)
808 R2=R2-1
810 GØTØ 804
820 R2=R2-1
822 R3=1-.5748646*R2+.9512363*R2↑2
824 R3=R3-.6998588*R2↑3+.4245549*R2↑4
```

```
826 R3=R3-.1010678*R2↑5
828 R=R1+LØG(R3)
830 RETURN
840 IF X>0 THEN 843
841 U7=0
842 GØTØ 844
843 U7=EXP(A1*LØG(X)+B1*LØG(1-X) +LØG(R4)+LØG(50000))
844 U8=U8+U7+U6
845 IF U3>0 THEN 850
846 IF U8<80000000 THEN 864
848 U3=X
850 IF U4>0 THEN 856
852 IF U8<90000000 THEN 864
854 U4=X
856 IF U5>0 THEN 864
858 IF U8<95000000 THEN 864
860 U5=X
864 U6=U7
870 RETURN
880 R4=10*R4
882 RETURN
900 R=1
902 FØR J=1 TØ B1+1
904 R=R*(A1+J)
906 NEXT J
908 FØR J=2 TØ B1
910 R=R/J
912 NEXT J
914 R4=R
920 GØTØ 245
930 S4=A1/(A1+B1)
932 IF S4<.975 THEN 960
933 IF S4<.99 THEN 936
934 IF S4=.99 THEN 936
935 GØTØ 962
936 S4=.975
944 R4=R4/10
946 FØR X=.9999 TØ .94999 STEP -.0001
948 GØSUB 840
950 NEXT X
952 R4=10*R4
960 RETURN
962 U6=EXP(A1*LØG(.9999)+B1*LØG(.0001)+LØG(R4)+LØG(5000))
963 U9=U6
964 R4=R4/10
965 FØR X=.9998 TØ .94999 STEP -.0001
966 GØSUB 840
968 NEXT X
970 U6=10*U6
```

```
972 R4=10*R4
974 FOR X=.949 TO 0 STEP -.001
976 GOSUB 840
977 NEXT X
978:"INT .9999 TO  1=."####
979 U8=100000000-U8
980 PRINT USING 978,U8*.00000001
981 U6=U9
982 U3=0
983 U4=0
984 U5=0
985 R4=R4/10
986 FOR X=.9998 TO .94999 STEP -.0001
987 GOSUB 840
988 NEXT X
989 GOTO 880
990 END
READY.
```

APPLICATION OF RESULTS

The results obtained from this study provide a means of assessing overall system reliability and subsystem and component reliability as well. The systems application will be outlined first; the simplified techniques to be used for the reliability analysis at lower levels will follow. The overall applications procedure is outlined in figure 25.

SYSTEMS APPLICATION

The assessment of systems level reliability using this methodology requires that a reasonable description of the system and the mission be available. The following five step procedure requires that system configuration and component identity be known and that mission profile parameters including number of cycles, cumulative operating time and elapsed mission time be available for every mission time point analyzed.

Fault tree development. At the system level the initial step requires the development of a fault tree for the system being analyzed. This study included the development of seven typical system fault trees that should be applicable (with minor modifications) to a broad range of propulsion systems. This analysis process need only continue down to those levels of the system for which models have been developed.

Model Quantification. The second step involves model identification and the determination of parameter values. Using the developed fault tree determine which expression contained in Volume I will be required. Assign the values to the identified input parameters corresponding to the mission times being analyzed. Note that component operating parameters (such as operating time and cycles) are independent of mission time. This allows the structuring of duty cycles that vary with the mission being assessed. Model identification and the appropriate parameter values for the time points being analyzed are then provided to the COMP1 computer program as requested (COMP1 is an interactive program).

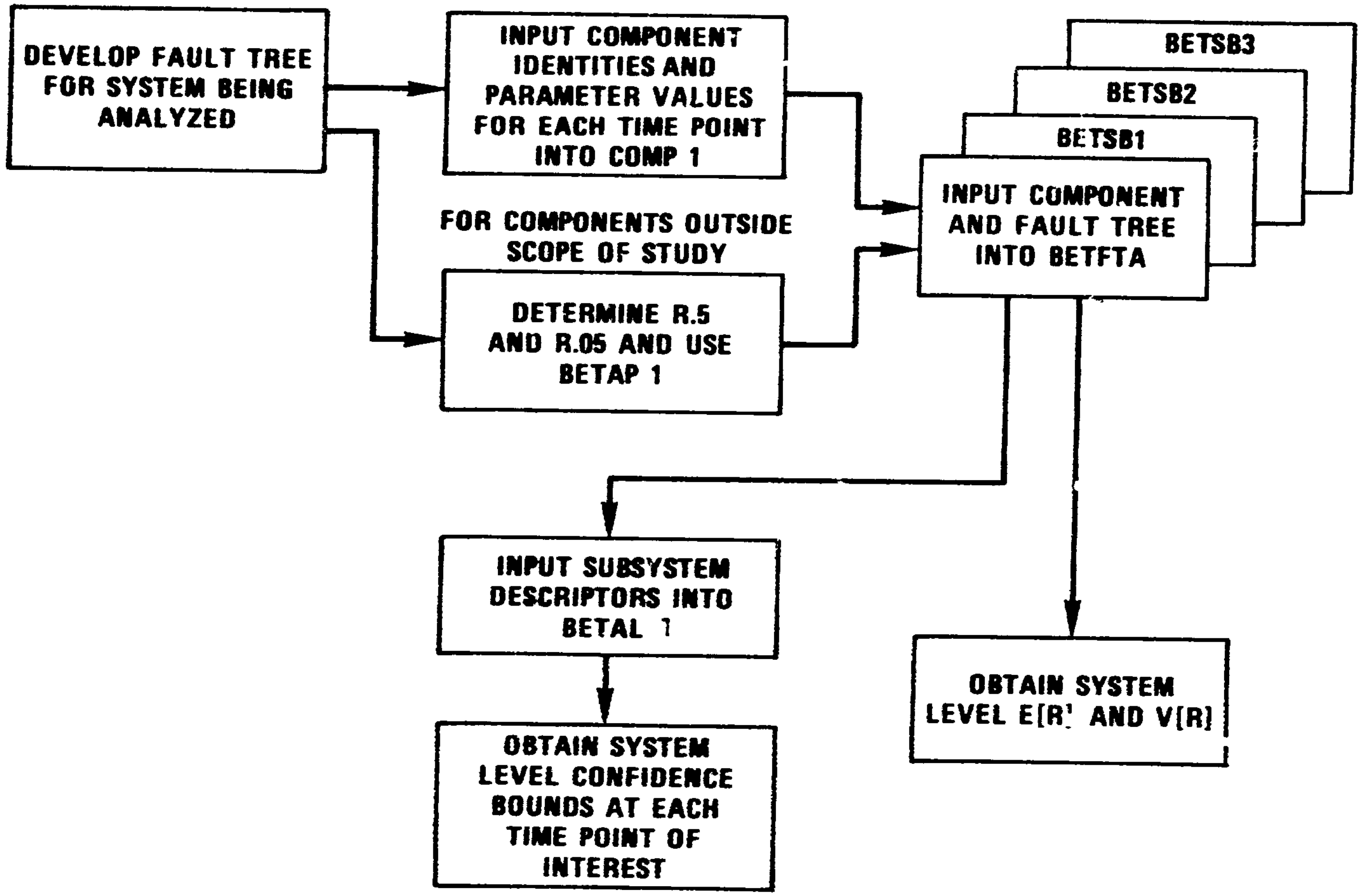

Figure 25. Methodology Application Procedure

If it is desired to consider components beyond the scope of the study in the system, the following procedure is used:

- Determine the median and 5% lower bound values of reliability of the component. While no model will be directly applicable from this study, the compendium of models provided and the approaches outlined should serve as a useful guide.

- Use the BETAP1 approximation technique to obtain α and β parameters of the Beta distribution used to aggregate to the subsystem and system levels.

System Level Analysis. From COMP1 and for BETAP1, the α and β parameters for the Beta distribution will be available. These parameters and the complete description of the fault tree (as described in the NUMERICAL PROCEDURES section) are provided to BETFTA if M out of N redundancies are not used in the system. For the special cases using M out of N redundancies, BETSB2 or BETSB3 are used as directed in the NUMERICAL PROCEDURES section. From COMP1 (or the iterative use of BESB2 or BETSB3) system level assessments of expected reliability $E\{R_{SYSTEM}\}$ and associated variance $V\{R_{SYSTEM}\}$ are obtained.

Reliability Estimate Bounds Computation. The results of COMP1 (or BETSB1, BETSB3) provide input for the BETAL1 program which computes the system level confidence bounds. It should be noted that BETAL1 can be used as soon as a level is reached in the fault tree where the remaining elements are connected by OR gates ( ) only.

As discussed in the CONCLUSIONS section a closed form systems level solution was not possible. To obtain a description of the system reliability variation with mission time, the last three steps in the above procedure must be repeated for each time point of interest.

Identification of Reliability and Uncertainty Drivers. If the results of the preceding calculations are entered on the system fault tree the reliability and uncertainty hierarchy will be readily observable. Those components most critical to system reliability and system uncertainty will be identified by tracing through the fault tree top to bottom.

In general it should be noted that the above procedures do not discriminate between systems and subsystems. The process is equally applicable to major subsystem. For complex systems it may prove desirable to treat major subsystems as systems to keep the process from becoming unweildy, leaving the aggregation to the systems level as a final step.

COMPONENT AND LIMITED SUBSYSTEM ANALYSIS

To assess subsystems of a simple nature (four components) or isolated components when aggregation to the system level is not desired. The following simplified procedure should be employed.

Determine and Quantify Component Models. Select the appropriate models from the RESULTS section. Identify the values of the required parameters for each time point being analyzed. For subsystem analysis, compute the reliability values at the median ($R_{.5}$) the 5% Lower Bound and the 95% ($R_{.95}$) Upper Bound. (This involves the use of λ's and α's subscripted with .5 for the median case. However, for the 5% lower bound case the λ's subscripted with .95 must be used along with α's subscripted by .05. Input these results into BETSB1 to obtain the expected subsystem reliability and variance $E\{R\}$ and $V\{R\}$, respectively. BETAL1 is not required since the bounds were already computed. It must be noted that while fractiles hold in transformation that is:

$$R_{.05} = f(\lambda_{.95}, \alpha_{.05})$$

$$R_{.5} = f(\lambda_{.5}, \alpha_{.5})$$

$$R_{.95} = f(\lambda_{.05}, \alpha_{.95})$$

the expected value does not

$$E\{R\} \neq f[E\{\lambda\}, \alpha_E \text{ ONLY}]$$

For analysis of individual components the mean ($R_{.5}$) the lower bound ($R_{.05}$) and the upper bound ($R_{.95}$) are computed using the models obtained from the results section. Then the following calculation will yield the expected value of reliability.

- Determine the standard deviation. From

$$R_{.05} = \exp[\mu_R - 1.645\ \sigma] \tag{1}$$

and

$$R_{.5} = \exp(\mu_R) \tag{2}$$

where μ_R = mean of the reliability distribution
σ = standard deviation of the reliability distribution,

obtain

$$\sigma = \frac{\mu_R - \ln(R_{.05})}{1.645} \tag{3}$$

and

$$\ln(R_{.5}) = \mu_R \tag{4}$$

From (3) and (4) obtain σ

$$\sigma = \frac{\ln(R_{.5}) - \ln R_{.05}}{1.645}$$

- Determine the expected reliability $E\{R\}$

$$E\{R\} = \exp[\mu + \frac{\sigma^2}{2}]$$

SUMMARY AND CONCLUSIONS

A credible, standardized basis for reliability comparison of thermochemical and electric propulsion concepts has been developed. The method employs detailed assessment of reliability at the component level and aggregates these estimates to provide a system level assessment using fault tree analysis as the system framework. Inherent in this approach is the capability of providing reliability estimates at all intermediate levels. Methodology credibility is assured through the quantification of estimate uncertainty at the component level and the systematic aggregation of this uncertainty to all higher levels.

It was not possible to develop a closed form analytical expression for the variation of system reliability as a function of time with the diverse set of component reliability models that resulted. To determine the time-wise system behavior, the methodology must be exercised at several time points and a curve must be fitted to the results. The principal obstacle to a straight forward system expression was fundamental: the inclusion of non-constant failure rates. It was concluded however that certain failure mechanisms (such as wear, fatigue, erosion) significant to the long duration missions of interest could not be realistically modeled with the constant failure rate approach. The imposition of this artificial restraint would not have to be justifiable merely on the grounds of mathematical tractability.

The results include the capability of identifying those components that are the greatest contributors to system failures. The determination of these "reliability drivers" cannot realistically be accomplished without reference to their position in the system configuration, their expected operating lives and duty cycles, and assessment of the uncertainty surrounding the reliability estimates themselves. With this information the methodology can also provide identification of those components that are the greatest contributors to system estimate uncertainty. Furthermore, a technique to develop test planning strategy to optimally reduce system uncertainty at minimum test costs has been generated and adapted for application to the system included in this study.

Finally, the developed methodology is modular throughout to facilitate revision and updating as additional reliability information becomes available. The component failure mode partitioning can be revised without requiring development of new component models. Changes at the component level can be made with minimum impact on the structure of the system fault trees. The functional approach taken in developing the system fault trees provides the flexibility of fault tree modification without the need to redevelop the entire fault tree structure. An example of this flexibility is provided by the thermochemical systems assessed. This category included three propulsion system concepts. For the purpose of fault tree development each system employed a different pressurization scheme (blowdown on the catalytic monoprop, pressurized surface tension on the electrothermal monoprop and regulated constant pressure on the biprop). In reality, any combination of pressurization scheme and propulsion concept is feasible. In an analagous manner the fault trees for these systems can be readily modified to reflect this interchangeability. Therefore nine system variations can be synthesized from the three baseline configurations used in this study.

GLOSSARY OF TERMS

E $\{R\}$ or E $\{P\}$	Expected value of reliability
E $\{R*R\}$ or E $\{P*P\}$	Expected value of the square of the reliability (the second moment about the origin).
V $\{R\}$	Variance associated with the expected value of reliability and is given by $V\{R\} = E\{R^2\} - E^2\{R\}$
ALPHA	Label used in computer programs developed in this study to identify the α parameter of the β-distribution
BETA	Label used in developed computer programs to identify the β parameter of the β-distribution
DELV and DELVAR	Used in program BETAL1 to represent "delta variance", the expected change in variance of the uncertainty distribution DELVAR is used at the system level, DELVAR at lower levels of aggregation
E(DELVAR)	Expected value of DELVAR
Independent Components	Components are regarded as being statistically independent if there is no reason to believe their (unknown) failure rates are alike. It is therefore possible for components to be independent even if the corresponding distribution parameters are alike.

Identical Components	Components are regarded as statistically identical if they are drawn from the same production lot because the initial <u>and</u> subsequent uncertainty descriptors remain alike (except for known differences in application stresses). See Appendix B for a discussion of independent/identical distinction.
Mission time =	Elapsed time from start of mission to the time at which reliability is being assessed. The units used are hours
Operating time =	Accumulated hours of actual operation at the time reliability is being assessed. The units used are hours.
Pressurized time =	Elapsed time from final charging and pressurization of component or subsystem to the time at which reliability is being assessed. For all the systems analyzed, pressurized time will be equal to or greater than mission time. The units are hours
Design cycle life =	Nominal number of operating cycle for which component was designed.
Design mission life =	Nominal mission length for which component was designed
Design operating life =	Nominal accumulative operative time for which component was designed.

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APPENDIX A

EXAMPLES

ELECTRONIC COMPONENTS RELIABILITY ESTIMATION PROCEDURES EXAMPLES

EXAMPLE 1

Diode, General Purpose, Silicon

Device Characteristics:

T_{MAX}	maximum junction temperature	175°C
T_S	temperature derating point	25°C
I_{MAX}	maximum rated average forward current	500 ma
	Rated voltage	200 v

Application Characteristics:

Heat sink temperature	25°C
Operating average forward current	200 ma
Applied voltage	140 v

Calculation of Expected Failure Rate

Part Failure Rate Model:

$$\lambda_p = \lambda_b(\pi_E \pi_Q \pi_A \pi_{S2} \pi_C) \text{ failures}/10^6 \text{ hr}$$

λ_b is found by table look-up (Table 2.2.4-6), * requiring temperature

$(T=T_C)$ and electrical stress ratio (S)

*All references to tables and figures in Examples 1, 2, and 3 can be found in MIL-HDBK-217B.

S is given by

$$S = \frac{I_{OP}}{I_{MAX}} (C.F.)$$

and C.F. = 1 for $T_{MAX} = 175^{o}C$ $T_{S} = 25^{o}C$

So that

$$S = \frac{200}{500} = .4$$

The table yields

$$_{b} = 0.0023$$

The -factors are obtained from Tables 2.2.4-1 through 2.2.4-5:

Factor		Value
π_E	Space, flight	1
π_Q	JANTXV quality	0.5
π_A	Small signal	1.0
π_{S2}	Voltage stress $\frac{140}{200} \times 100 = 70\%$	0.75
π_C	Metallurgically bonded	1

thus

$$\lambda_p = 0.0023 \cdot 1 \cdot 0.5 \cdot 1 \cdot 0.75 \cdot 1 = 0.0008625 \text{ failures}/10^6 \text{ hr}$$

Uncertainty Expression

As noted earlier, the lognormal distribution model with square of coefficient of variation

$$\eta^2 = 2.74$$

will be used to estimate and describe uncertainties surrounding estimates of constant failure rates for electronic devices.

For the diode, we have

$$E\{\lambda\} = 0.0008625 \text{ failures}/10^6 \text{ hr}$$

since

$$\eta^2 = e^{\sigma^2} - 1 = 2.74$$

We have

$$\sigma^2 = \ln 3.74 = 1.3191$$

$$\sigma = 1.149$$

but

$$E\{\lambda\} = e^{\quad +1/2 \quad 2}$$

$$\mu = \ln E \quad - 1/2 \quad 2 = -7.715$$

The uncertainty distribution for the diode thus is lognormal with $\mu = -7.715$, $\sigma = 1.149$. This in turn yields

$$\text{Lower bound, } F_{.05} = e^{\mu-1.645} = 0.00007 \text{ failures}/10^6 \text{ hr}$$

$$\text{Median, } M = e^{\mu} = 0.00045$$

$$\text{Upper bound, } F_{.95} = e^{\mu+1.645\sigma} = 0.00295.$$

Alternatively, but less comprehensively, the diode failure rate could be said to be $0.0086 \, {}^{+243\%}_{-\ 92\%} \times 10^{-6}$.

For nonelectronic devices, the uncertainty estimates (coefficient of variation) are adjusted to reflect information gained (e.g., by detailed stress analysis) and additional uncertainties introduced (e.g., by extrapolation to different device types or use of large and arguable environmental correction factors) during analysis. This is unnecessary for electronic devices because gains and losses in MIL-HDBK-217B analyses are considered to be balanced.

EXAMPLE 2

Capacitor, Tantalum, Solid

Device Characteristics

MIL-C-39003, level P

20v, 10 F

Application Characteristics:

T	Ambient Temperature	25°C
S	Applied voltage	10v
SR	Circuit series resistance	5 ohms

Calculation of Expected Failure Rate

Part Failure Rate Model:

$$\lambda_p = \lambda_b(\pi_E \cdot \pi_{SR} \cdot \pi_Q) \text{ failures}/10^6 \text{ hr}$$

λ_b, π_E, and π_Q are found from Tables 2.6.5-4, 2.6.5-1, and 2.6.5-3, respectively:

$$\lambda_b = 0.010$$

$$\pi_E = 1$$

$$\pi_Q = 0.3$$

The relative circuit resistance is 5/10 ohms/volt. Interpolating in Table 2.6.5-2 yields $\pi_{SR} = 0.5$. Thus

$$\lambda_p = 0.010 \cdot 1 \cdot 0.5 \cdot 0.3 \text{ failures}/10^6 \text{ hr.}$$
$$= 0.0015 \text{ failures}/10^6 \text{ hr.}$$

Uncertainty Expression

Proceeding as in Example 1, we obtain:

$$E\{\lambda\} = e^{\mu+1/2\sigma^2} = 0.0015$$

since σ is fixed for constant η^2,

$$\mu = \ln E\{\lambda\} - .6595 = -7.162$$

and the uncertainty distribution for the capacitor is lognormal with $\mu = -7.162$, $\sigma = 1.149$. This in turn yields

$$F_{.05} = 0.00012 \text{ failures}/10^6 \text{ hr.}$$
$$M = 0.00078$$
$$F_{.95} = 0.00513$$

In tolerance form, the capacitor failure rate could be said to be $0.0015 \begin{smallmatrix} +242\% \\ -\ 92\% \end{smallmatrix} \times 10^{-6}$; for fixed η^2, percentage tolerances referenced to the expected value also are fixed in the lognormal distribution.

EXAMPLE 3

Transformer, Power

Device Characteristics:

MIL-T-27 Grade 4, Class R, Family 1

Hermetically Sealed

28/240v, 20va

Weight 1.5 lbs.

Application Characteristics:

T_A	ambient (radiation sink) temperature	$25^{\circ}C$
	weighted average load	16va

CALCULATION OF EXPECTED FAILURE RATE

Part Failure Rate Model:

$$\lambda_p = \lambda_b (\pi_E \cdot \pi_f) \text{ failures}/1.0^6 \text{ hr}$$

λ_b is found from

$$\lambda_b = Ae^x$$

where

$$x = \left(\frac{T_{HS} + 273}{N_T}\right)^G$$

T_{HS} = Hot spot temperature (^{o}C.)

From Table 2.7-1:

$$A = 7.2 \cdot 10^{-4}$$

$$N_T = 352$$

$$G = 14$$

With the available data, it is necessary to enter Figure 2.7-4 for weight 1.5 lbs, input 20 watts (16 VA output,unity power factor, 80 percent efficiency). This yields an average temperature rise

$$\Delta_T = 32^o \text{ C.}$$

From paragraph 2.7.1.2

$$T_{HS} \approx T_A + 1.1\,(\Delta T) = 60^{\circ}\,C$$

then

$$x = {\frac{60 + 273}{352}}^{14} = 0.46$$

$$\lambda_b = 7.2 \cdot 10^{-4} \cdot 0.46 = 3.3 \times 10^{-4}.$$

From Tables 2.7-3 and 2.7-4, we obtain

$$\pi_f = 8$$

$$\pi_E = 1$$

so that

$$\lambda_p = 3.3 \times 10^{-4} \cdot 8 \cdot 1 \text{ failures}/10^6 \text{ hours}$$

$$= .0026 \qquad \text{failures}/10^6 \text{ hours}$$

<u>Uncertainty Expression</u>

Proceeding as before, we would obtain:

$$\mu = -6.612$$

$$F_{.05} = 0.0002 \text{ failures}/10^6 \text{ hr.}$$

$$M = 0.0013$$

$$F_{.95} = 0.0089$$

However, transformers are among the least standardized electronic devices and are sensitive to the relatively frequent assembly and processing variations and errors reflected in Table 2.7-3. In addition, the failure rate is rather sensitive to the hot spot temperature, T_{HS}, which was crudely approximated. In view of this, an exception to the stated procedure for electronic part uncertainties is in order.

Table 2.7-3 indicates a 5:1 ratio between upper and lower values of π_f taking these values to define a 95 percent interval (lognormal) and setting 4 standard deviations equal to the natural logarithm of 5 yields

$$\sigma_E = 0.4$$

A similar contribution by T_{HS} uncertainties leads to a new overall estimate for the aggregate standard deviation of the uncertainty distribution:

$$\sigma^1 = \sqrt{\sigma^2 + \sigma_E^2 + \sigma_{HS}^2}$$

$$= \sqrt{1.3191 + 0.16 + 0.16} = 1.28$$

The nature of these changes is such that λ_p remains the best estimate of $E(\lambda)$. The modified uncertainty distribution descriptors thus become

$$\mu^1 = -6.771$$

$$F_{.05} = 0.0001 \text{ failures}/10^6 \text{ hours}$$

$$M = 0.0011$$

$$F_{.95} = 0.0094$$

Wear-Out Effects

The preceding estimates considered only constant-failure-rate effects. Transformers are subject to thermal aging of insulation and hence to a well-defined "wear-out" pattern. To determine whether it is necessary to take into account, it is desirable to start with conservative estimates of the wear-out distribution.

At maximum rated hot-spot temperature, transformer wear-out life can be described by a normal distribution with μ_{105} = 10,000 hours, $\sigma_{105} \leq$ 2,000 hours.

For class R insulation, the maximum temperature is 105° C. Previously, T_{HS} was estimated to be 60° C. Since we are scaling down from 105° C, it is conservative to use 10° C rather than 7° C in the "rule of thumb" (or Arrhenius equation) for a factor of 2 in life expectancy. Thus, the 60° C life expectancy is

$$\mu_{60} = 2^{\frac{105-60}{10}} \cdot \mu_{105} \approx 225,000 \text{ hours}$$

The coefficient of variation $(\frac{\sigma}{\mu})$ is unaffected by scaling, so that

$$\sigma_{60} \leq 45,000 \text{ hours}$$

The longest mission under consideration is 10 years = 87,600 hours = $\mu_{60} - 4\ \sigma_{60}$. Pessimistically, the probability of failure due to wear-out is ~ 0.000032.*

*From tables of integrals of the normal distribution; for such large multiples of σ, it is desirable to use a detailed table such as the National Bureau of Standards' AMS23. It should be emphasized, however, that results from the extreme tails of a distribution are always subject to question. It is rare that physical reality can be represented credibly by theoretical models at the extremes.

For comparison, the 87,600-hour failure probabilities (exponential) due to $F_{.05}$, λ_p, and $F_{.95}$, respectively, are

$$Q_{.05} \approx 0.000009$$

$$\hat{Q} \approx 0.00023$$

$$Q_{.95} \approx 0.0008$$

(In all cases, a 100 percent duty cycle has been assumed.)

In this example, the wear-out contribution is dominant compared to the constant-failure-rate contribution at $F_{.05}$, small compared to the best estimate of the latter, and negligible compared to the $F_{.95}$ contribution.

The wear-out contribution becomes smaller (both absolutely and relatively) under any of the following:

- A less conservative estimate of wear-out
- A reduced duty cycle
- A shorter mission
- Any earlier time in a 10-year mission

In view of these considerations, and in light of the fact that system-level use of device failure rates concentrates on the expected and $F_{.95}$ values, wear-out effects should be disregarded here. However, wear-out life may be the limiting factor for other components and should not be disregarded without analytical justification. As noted earlier, physical demonstration of adequate life expectancy sometimes will be necessary. Reliability prediction using MIL-HDBK-217B data is not an adequate tool when there is reason to expect clustered failures within desired mission durations.

METHODOLOGY APPLICATIONS

EXAMPLE I MERCURY ION SYSTEM

1. Mission: Duration = 5 yrs = 43,800 hrs
   Cumulative Operating Time = 22.876×10^{6} sec = 6354 hrs
   Number of Cycles = 1826

2. Evaluation Point t_m = 5 yrs (End of Mission) = 43800 hrs
   t_{op} = 6354 hrs
   N = 1826

3. Component/Failure Mode Identity - Obtain From Fault Tree
   Component/Failure Mode Code Identity - Obtain From Table 9, Vol II

Component/Failure Mode	Code
Bladder Leak/Rupture	BB
Propellant Line Leak/Rupture	FL
Propellant Fill Valve Leak/ Rupture	FV1
Propellant Tank Half, Leak/ Rupture	PR
Pressurant Fill Valve Leak/ Rupture	FV1
Pressurant Tank Leak/Rupture	PT
Tank Heater Failure	HLTV
Line Heater Failure	HLTV
PCC Switch Fails Active	SA
PCC Switch Fails Passive	SP
PCC Failure Mercury Ion	MPC
Liquid Mercury to Cathode -Use Vaporizor Leakage	VL
Vaporizer Heater Failure	VH
Vaporizer Clogged	VC
Feed Line Leak/Rupture	FL
Loss of Electrical Isolation	II
Discharge Chamber Malfunction	DC
Cathode Assembly out of Tolerance Use Cathode, Hollow	HC
Neutralizer Cathode out of Tolerance	NC
Neutralizer Vaporizer	NV
Neutralizer Isolator	NI

Gimbal Thrust Vectoring

Lower Support	LS
Upper Support	US
Linear Actuator	LA
Motor and Gearing	MG

4. Enter Program COMP1 with the preceding codes and appropriate cycles, mission times and operating times. For this case as stated in 2. above

$$N = 1826 \text{ cycles}$$
$$t_{op} = 6354 \text{ hrs}$$
$$t_m = 43800 \text{ hrs}$$

COMP1 output is shown on the following pages. Note each computation result is followed by request for second data entry for the component. This feature is exercised when multiple time points in system life are being analyzed.

```
 76/12/14. 10.36.07.
FROGRAM . COMP1

OUTPUT FORMAT IS
R.05      R.5       ALPHA       BETA

COMPONENT CODE?(ZZ=END)
? BB
PRESS. TIME=? (O=END)
? 43800
   .978552     .998945     67.9354     -.7013
PRESS. TIME=?
? 0

COMPONENT CODE?(ZZ=END)
? FL
OPTIME=? (O=END)
? 6354
   .998730     .999520    *4110.8949     2.2724
OPTIME=?
? 0

COMPONENT CODE?(ZZ=END)
? FV1
PRESS. TIME=? (O=END)
? 43800
   .985952     .999601     93.8530     -.7616
PRESS. TIME=?
? 0

COMPONENT CODE?(ZZ=END)
? PR
PRESS. TIME=? (O=END)
? 43800
   .981127     .998118     92.5260     -.5621
PRESS. TIME=?
? 0

COMPONENT CODE?(ZZ=END)
? PT
SAME AS PR
PRESS. TIME=? (O=END)
? 43800
   .981127     .998118     92.5260     -.5621
PRESS. TIME=?
? 0
```

```
COMPONENT CODE?(ZZ=END)
? HLTV
MISSION TIME=? (0=END)
? 43800
    .992625      .999085     259.9071      -.4869
OPTIME=?
? 0

COMPONENT CODE?(ZZ=END)
? SA
NO. CYCLES =? (0=END)
? 200
    .999996      1.00000     *407623.0801      -.5416
NO. CYCLES=?
? 0

COMPONENT CODE?(ZZ=END)
? SP
SAME AS SA
NO. CYCLES =? (0=END)
? 200
    .999996      1.00000     *407623.0801      -.5416
NO. CYCLES=?
? 0

COMPONENT CODE?(ZZ=END)
? MPC
MISSION TIME=? (0=END)
? 43800
    .940275      .989938     35.4690      -.3431
OPTIME=?
? 0

COMPONENT CODE?(ZZ=END)
? VL
 INPUT OPTION
1= FIXED CYCLES/OP.HR., 2=SEPARATE
? 2
CYCLES =? (0=END)
? 1826
OPTIME=? (0=END)
? 6354
    .919492      .991620     20.5070      -.5580
CYCLES =? (0=END)
? 0
```

```
COMPONENT CODE?(ZZ=END)
? VH
OPTIME=? (O=END)
? 6354
   .982803      .997462     119.930[illegible]      -.4098
OPTIME=?
? 0

COMPONENT CODE?(ZZ=END)
? VC
OPTIME=? (O=END)
? 6354
   .979966      .998356     82.2047       -.6117
OPTIME=?
? 0

COMPONENT CODE?(ZZ=END)
? FL
OPTIME=? (O=END)
? 6354
   .998730      .999520     *4110.8949     2.2724
OPTIME=?
? 0

COMPONENT CODE?(ZZ=END)
? II
OPTIME=? (O=END)
? 6354
   .888034      .990866     13.1973       -.6829
OPTIME=?
? 0

COMPONENT CODE?(ZZ=END)
? DC
OPTIME=? (O=END)
? 6354
   .943165      .996188     26.3681       -.6557
OPTIME=?
? 0

COMPONENT CODE?(ZZ=END)
? HC
OPTIME=? (O=END)
? 6354
   .650401      .894764     7.6686        1.1666
OPTIME=?
? 0
```

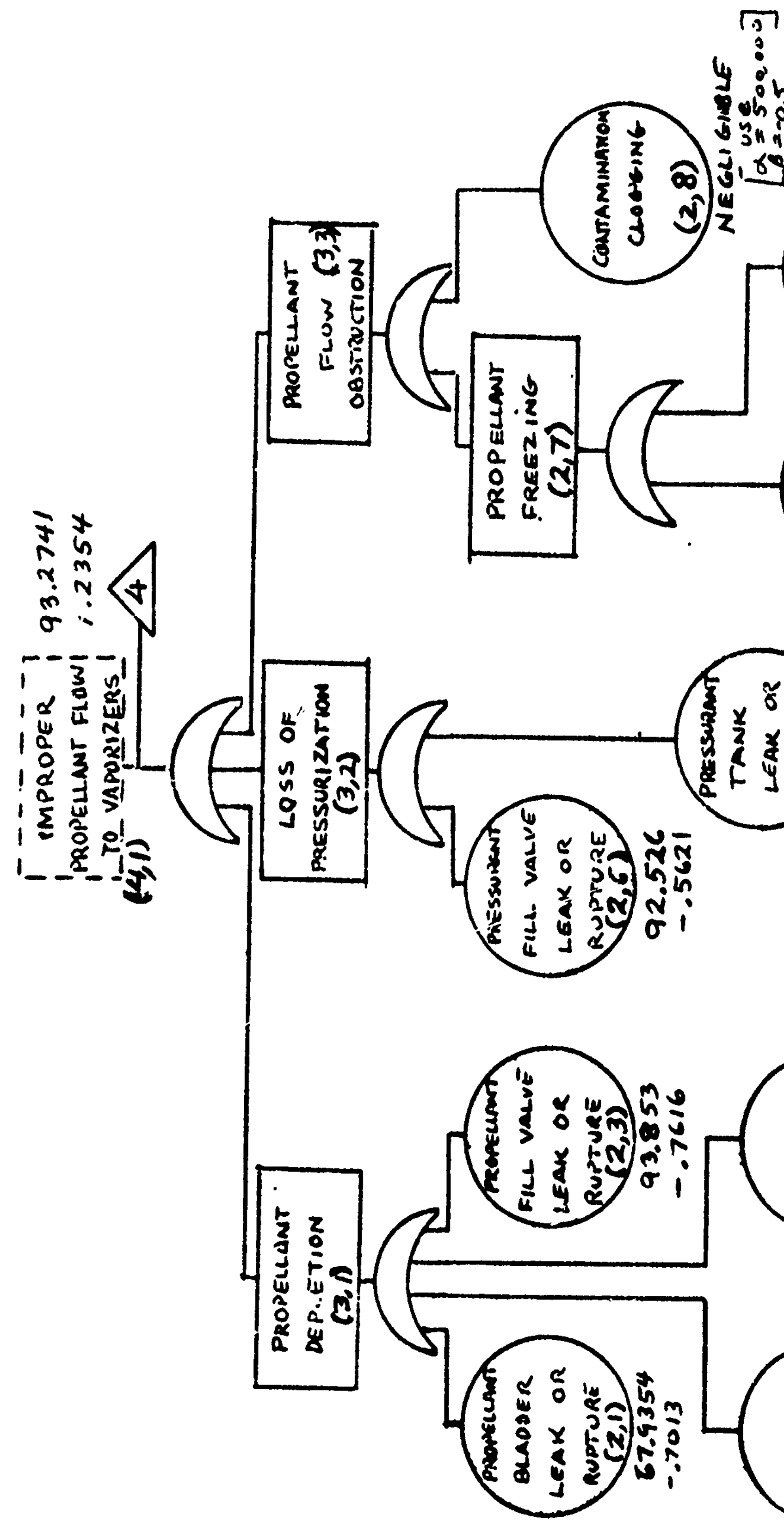
```
CØMPØNENT CØDE?(ZZ=END)
? NC
ØPTIME=? (O=END)
? 6354
   .650401      .894764      7.6686      1.1666
ØPTIME=?
? 0

CØMPØNENT CØDE?(ZZ=END)
? NV
CLØG & LEAK CØMBINED
( TØ SEPARATE, USE VC AND VL )
 INPUT ØPTIØN
1= FIXED CYCLES/ØP.HR., 2=SEPARATE
? 2
CYCLES =? (O=END)
? 1826
ØPTIME=? (O=END)
? 6354
   .901128      .975434      29.8529      1.0432
CYCLES =? (O=END)
? 0

CØMPØNENT CØDE?(ZZ=END)
? NI
ØPTIME=? (O=END)
? 6354
   .888034      .990866      13.1973      -.6229
ØPTIME=?
? 0

CØMPØNENT CØDE?(ZZ=END)
? LS
ØPTIME=? (O=END)
? 6354
   .950257      .996638      30.4268      -.6538
ØPTIME=?
? 0

CØMPØNENT CØDE?(ZZ=END)
? US
ØPTIME=? (O=END)
? 6354
   .966885      .998153      44.5823      -.6841
ØPTIME=?
? 0
```

```
COMPONENT CODE?(ZZ=END)
? LA
OPTIME=? (O=END)
? 6354
    .889097      .988251      14.4370      -.5572
OPTIME=?
? 0

COMPONENT CODE?(ZZ=END)
? MG
OPTIME=? (O=END)
? 6354
    .889097      .988251      14.4370      -.5572
OPTIME=?
? 0

COMPONENT CODE?(ZZ=END)
? ZZ
NO SUCH COMPONENT

SBU        5.601 UNTS.

RUN COMPLETE.
BYE

S229333 LOG OFF  10.55.01.
SBU         12.201
TIO =      3485

P
```

5. Enter BETFTA with COMP1 results and fault tree logic. In this example the fault tree will be traced from the component/failure mode level up to the overall systems level. While BETFTA has the capacity to compute the entire fault tree in one sequence of operations, for the sake of clarity each major portion of the fault tree was analyzed as an independent entity.

The first portion shown "Improper Propellant Flow to Vaporizers" will be used to identify the numerical entries identifying fault tree events and magnitudes of the α and β parameters of the beta distribution. These values (α, β) were taken directly from the output of COMP1. They appear with their associated event; α is given first with β following immediately below. The numbers contained in parenthesis are the event code for use in BETFTA. As described in the BETFTA outline, the first number identifies the fault tree level (counted from the bottom up) to which the event belongs. The second entry identifies the location (counting left to right) of the event in the level. Therefore, the set (2,3) uniquely identifies "Propellant Fill Valve Leak or Rupture" as the third event on the second level in the fault tree "improper propellant flow to vaporizers". Note that "Contamination Clogging" was <u>not</u> given an identifying code. It was assessed as being negligible and can be disregarded in the remainder of the analysis (the degenerate one-on-one tree that results from the elimination of this event can be accepted by the BETFTA program.

The level 1 and 2 events obtain their values from COMP1 output; the level 4 event obtains its value from BETFTA. Although not shown on the fault tree, BETFTA also computes the α and β values of intermediate level events, in this case level 3 events. These appear immediately after the "Gate Type" response, preceded by the appropriate event code, in the BETFTA output following the fault tree. The remainder of the Mercury Ion System Computation follows in the same format.

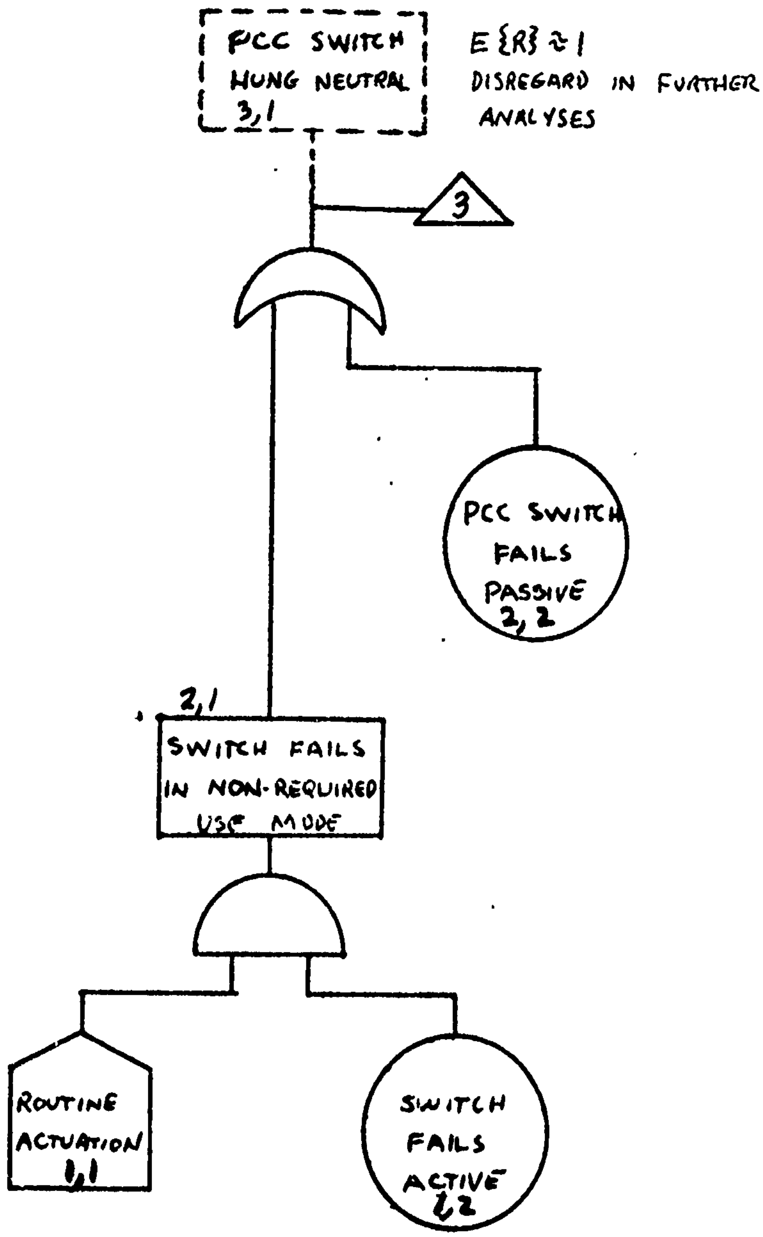

IMPROPER PROPELLANT FLOW TO VAPORIZERS (4,1)
93.2741
1.2354
4
PROPELLANT DEPLETION (3,1)
LOSS OF PRESSURIZATION (3,2)
PROPELLANT FLOW OBSTRUCTION (3,3)
PROPELLANT FREEZING (2,7)
PROPELLANT BLADDER LEAK OR RUPTURE (2,1)
67.9354
-.7013
PROPELLANT LINE LEAK OR RUPTURE (2,2)
4110.8949
2.2724
PROPELLANT FILL VALVE LEAK OR RUPTURE (2,3)
93.853
-.7616
PROPELLANT TANK LEAK OR RUPTURE (2,4)
92.526
-.5621
PRESSURANT TANK LEAK OR RUPTURE (2,5)
93.853
-.7616
PRESSURANT FILL VALVE LEAK OR RUPTURE (2,6)
92.526
-.5621
CONTAMINATION CLOGGING (2,8)
NEGLIGIBLE
USE α = 500,000 β = -0.5
TANK HEATER FAILURE (1,1)
259.9071
-.4869
LINE HEATER FAILURE (1,2)
259.9071
-.4869

```
ROGRAM   BETFTA

90000 DATA 259.9071,-.4869,259.9071,-.4869
90004 DATA 67.9354,-.7013,4110.8949,2.2724,93.853,-.7616,92.526,-.5621
90006 DATA 92.853,-.7615,92.526,-.5621
90008 DATA 500000,-.5
99999 END
READY.

FOR EXPLANATION LIST 80000
HOW MANY LEVELS?
? 4
EVENTS? (LOWEST FIRST) (SINGLE ASSUMED AT TOP)
? 2
? 8
? 3
DESTINATION?
 1  1 ? 7
 1  2 ? 7
 2  1 ? 1
 2  2 ? 1
 2  3 ? 1
 2  4 ? 1
 2  5 ? 2
 2  6 ? 2
 2  7 ? 3
 3  1 ? 1
 3  2 ? 1
 3  3 ? 1
CONDITIONALS?(0,0=SKIP)
? 0,0
GATE TYPES
 2  7 ? 3
 3  1 ? 1
 3  2 ? 1
 3  3 ? 1
 4  1 ? 1
```

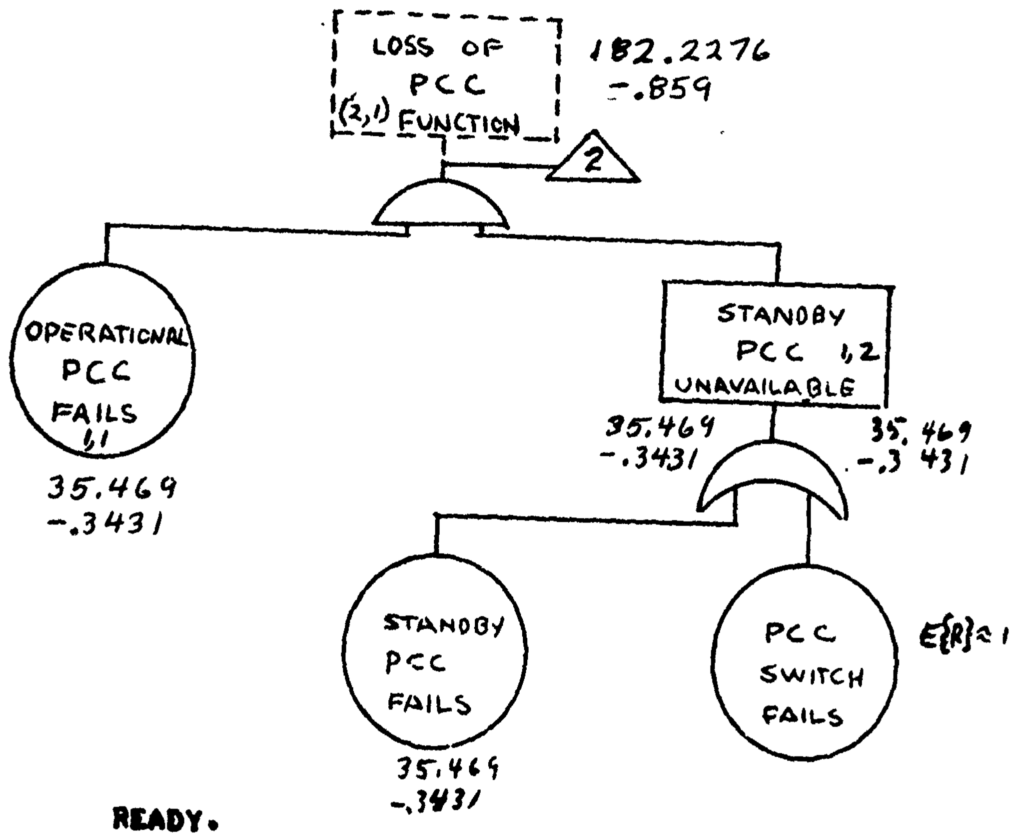
I	J	α	β
2	7	129.575	-.486901
3	1	87.0179	8.93594E-2
3	2	92.4872	-.323599
3	3	129.608	-.486639
4	1	93.2741	1.23518

INTERMEDIATE (LEVEL 3) RESULTS IDENTIFIED BY (I,J) CODE

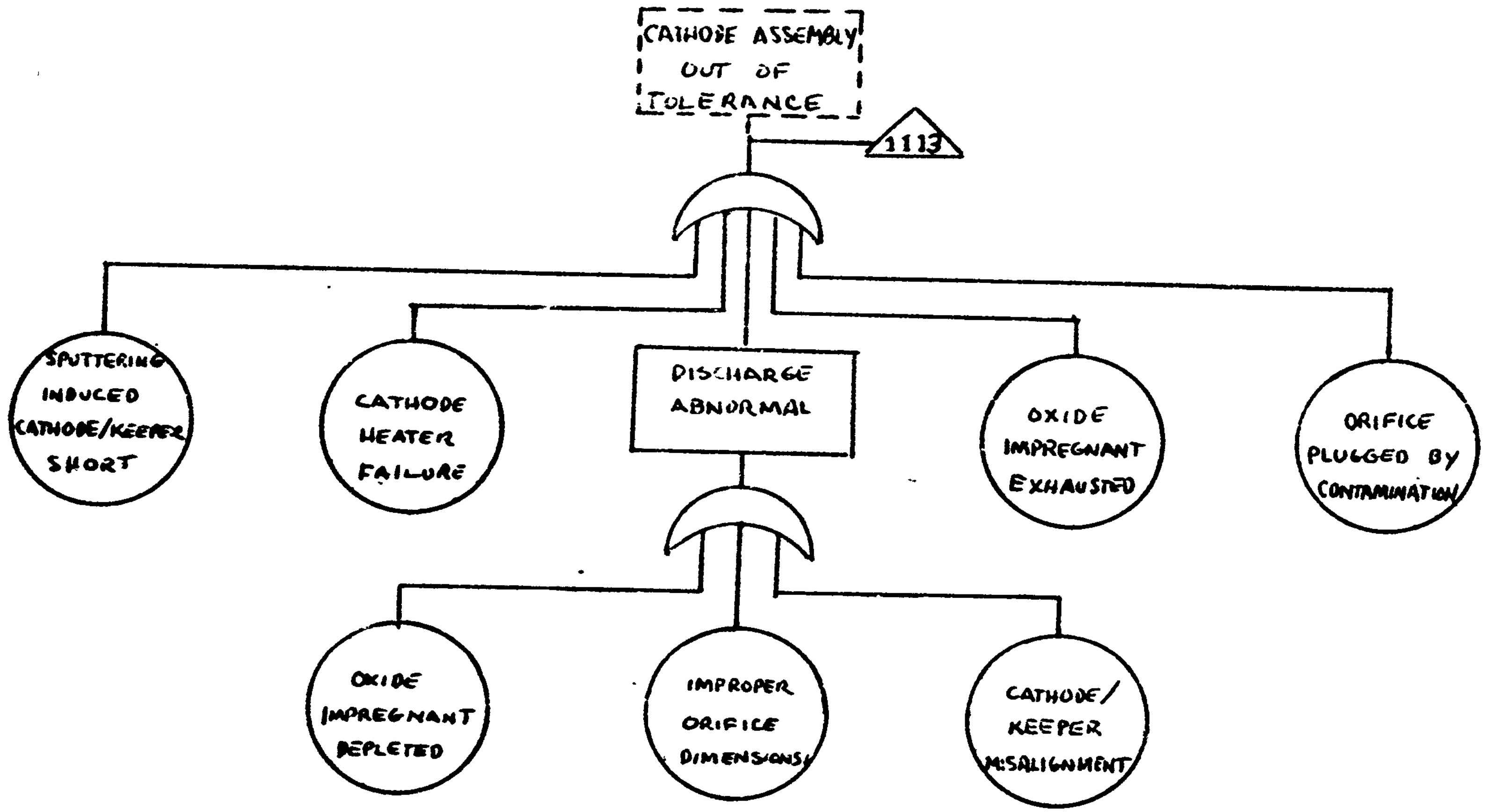
```
SYSTEM (ITERATION  1)
ALPHA    BETA    E(P)     E(P*P)    V(P)

93.2741  1.2352 .976840  .954448  .00023202

RUN COMPLETE.
```



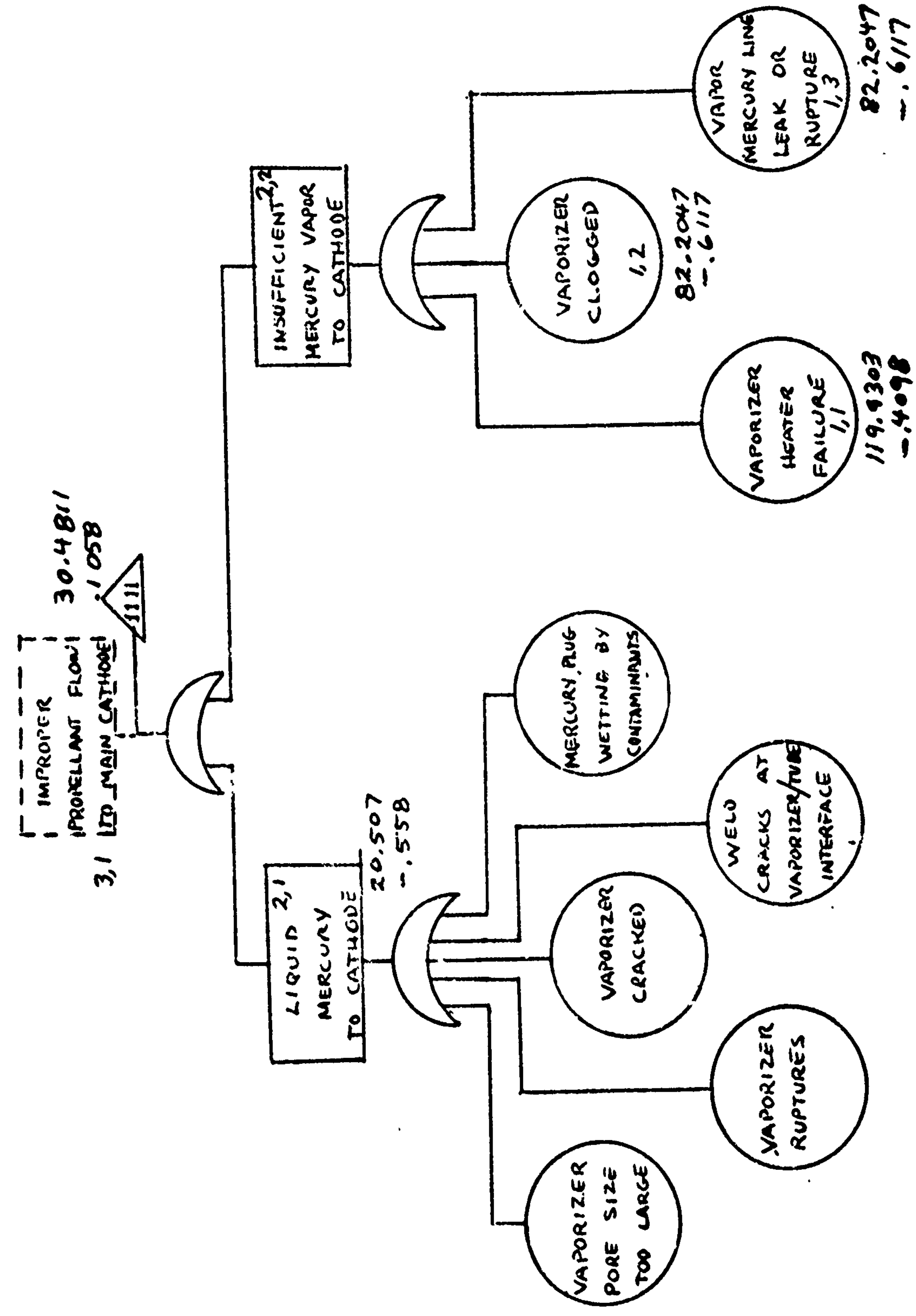
NOTE THE RESULTS FROM THE COMP 1 MODELS (SA AND SP) FOR THE PCC SWITCH INDICATE A RELIABILITY APPROACHING 1.0. IT WILL NOT BE CONSIDERED FURTHER DUE TO ITS NEGLIGIBLE IMPACT RELATIVE TO THE REMAINING COMPONENTS IN THE SYSTEM



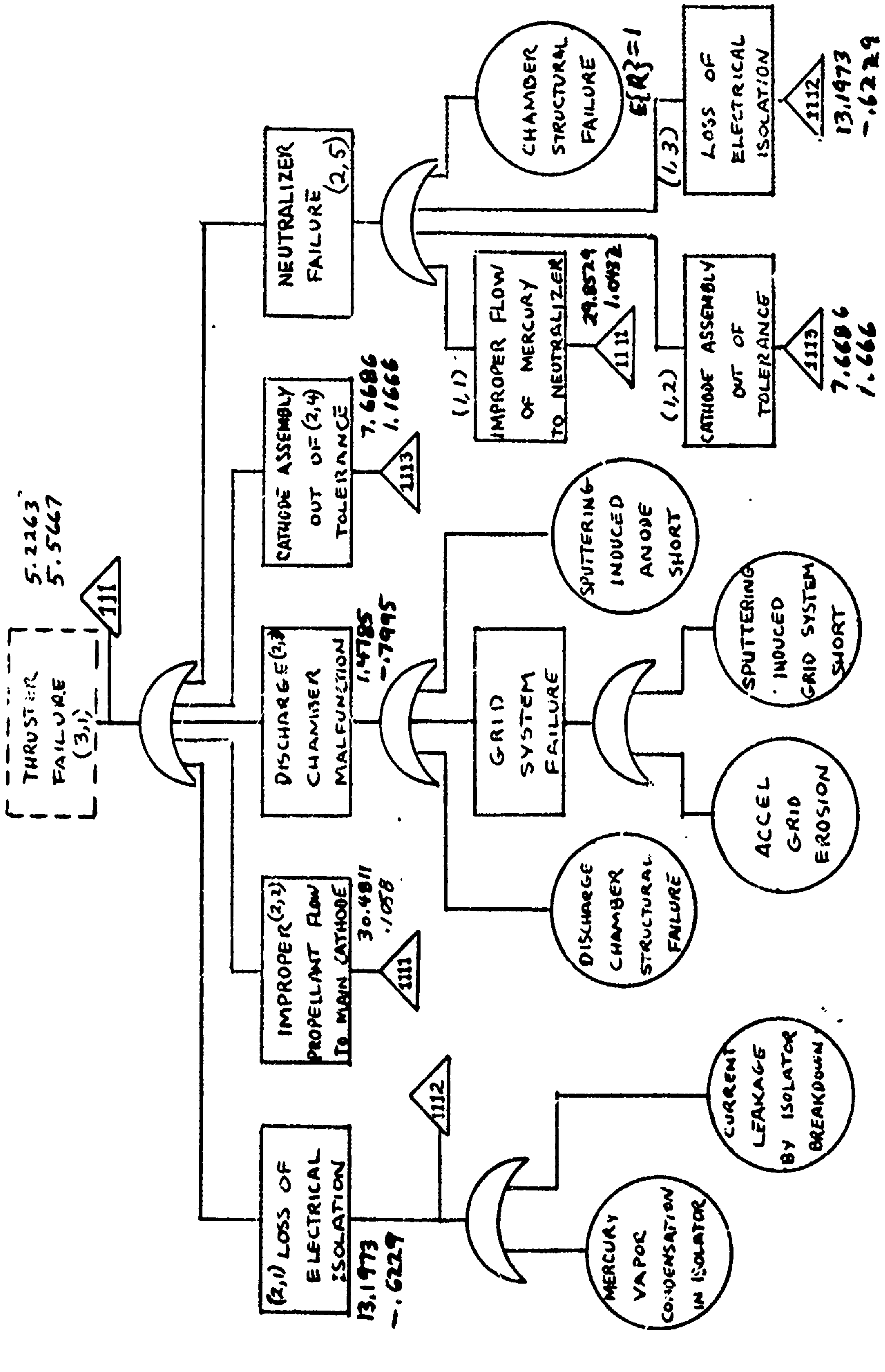

```
READY.
90000 DATA 35.469,-.3431,35.469,-.3431
RUN

 76/12/14. 15.14.59.
PROGRAM   BETFTA

FOR EXPLANATION LIST 80000
HOW MANY LEVELS?
? 2
EVENTS? (LOWEST FIRST) (SINGLE ASSUMED AT TOP)
? 2
DESTINATION?
 1   1 ? 1
 1   2 ? 1
CONDITIONALS?(0,0=SKIP)
? 0,0
GATE TYPES
 2   1 ? 4

 2   1   182.228 -.858999
SYSTEM (ITERATION  1)
ALPHA    BETA    E(P)       E(P*P)      V(P)

*182.2276  -.8590 .999231  .998467  .00000417
```



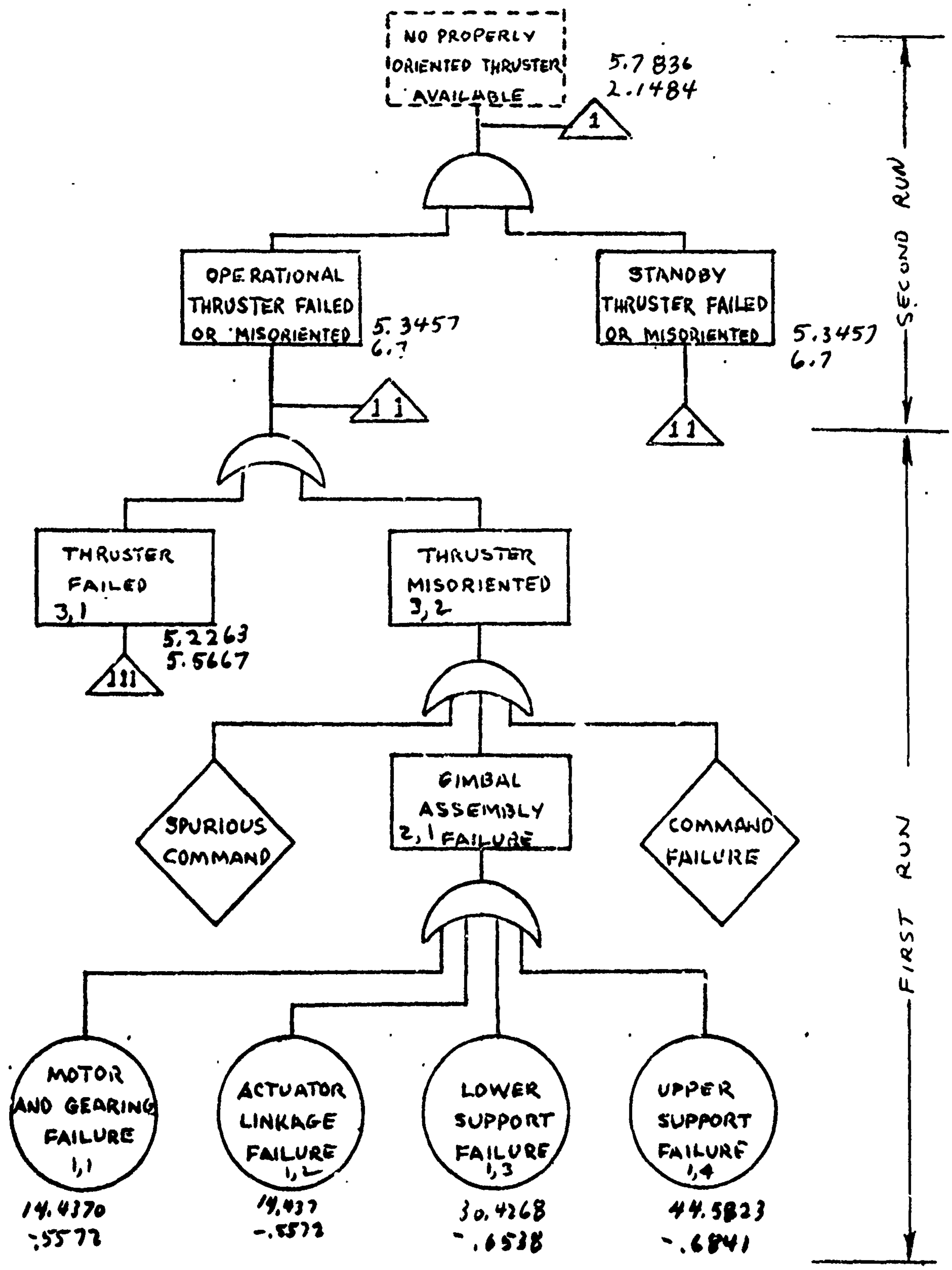
NOTE THERE WERE NO MODES DEVELOPED AT THESE LEVELS DUE TO DATA LIMITATIONS. THIS BREAKDOWN OF THE CATHODE IS PROVIDED FOR POSSIBLE FUTURE USE AS ADDITIONAL DATA BECOMES AVAILABLE


IMPROPER PROPELLANT FLOW TO MAIN CATHODE
3,1
30.4811
.1058
1111
LIQUID MERCURY TO CATHODE 2,1
20.507
-.558
INSUFFICIENT MERCURY VAPOR TO CATHODE 2,2
VAPORIZER HEATER FAILURE 1,1
119.9303
-.4098
VAPORIZER CLOGGED 1,2
82.2047
-.6117
VAPOR MERCURY LINE LEAK OR RUPTURE 1,3
82.2047
-.6117
VAPORIZER PORE SIZE TOO LARGE
VAPORIZER RUPTURES
VAPORIZER CRACKED
WELD CRACKS AT VAPORIZER/TUBE INTERFACE
MERCURY PLUG WETTING BY CONTAMINANTS

```
PROGRAM   BETFTA

90000 DATA 119.9303,-.4098,82.2047,-.6117,82.2047,-.611
90002 DATA 20.507,-.558
99999 END
READY.
PROGRAM   BETFTA

FOR EXPLANATION LIST 80000
HOW MANY LEVELS?
? 3
EVENTS? (LOWEST FIRST) (SINGLE ASSUMED AT TOP)
? 3
? 2
DESTINATION?
 1   1 ? 2
 1   2 ? 2
 1   3 ? 2
 2   1 ? 1
 2   2 ? 1
CONDITIONALS?(0,0=SKIP)
? 0,0
GATE TYPES
 2   2 ? 1
 3   1 ? 1

 2   2   91.7731   .324943
 3   1   30.4811   .105821


SYSTEM (ITERATION  1)
ALPHA    BETA    E(P)      E(P*P)     V(P)

30.4811    .1058 .966066   .934259   .00097606


 END OF DATA  AT  58
BASIC EXECUTION ERROR

SBU       0.719 UNTS.

RUN COMPLETE.
LIST,90000

 76/12/14. 15.36.00.
```


THRUSTER FAILURE (3,1)
111
5.2263
5.5667
(2,1) LOSS OF ELECTRICAL ISOLATION
13.1973
-.6229
1112
MERCURY VAPOR CONDENSATION IN ISOLATOR
CURRENT LEAKAGE BY ISOLATOR BREAKDOWN
IMPROPER (2,2) PROPELLANT FLOW TO MAIN CATHODE
30.4811
.1058
1111
DISCHARGE (3,3) CHAMBER MALFUNCTION
1.4785
-.7995
DISCHARGE CHAMBER STRUCTURAL FAILURE
GRID SYSTEM FAILURE
SPUTTERING INDUCED ANODE SHORT
ACCEL GRID EROSION
SPUTTERING INDUCED GRID SYSTEM SHORT
CATHODE ASSEMBLY OUT OF (2,4) TOLERANCE
7.6686
1.1666
1113
NEUTRALIZER FAILURE (2,5)
(1,1) IMPROPER FLOW OF MERCURY TO NEUTRALIZER
29.8529
1.0932
1111
(1,2) CATHODE ASSEMBLY OUT OF TOLERANCE
1113
7.6686
1.666
CHAMBER STRUCTURAL FAILURE
E[R]=1
(1,3) LOSS OF ELECTRICAL ISOLATION
1112
13.1973
-.6229

```
90000 DATA 29.8529,1.0432,7.6686,1.666,13.1973,-.6229
90002 DATA 13.1973,-.6229,30.4811,.1058,1.4785,-.7995
90004 DATA 7.6686,1.1666
RUN
PROGRAM   BETFTA

FOR EXPLANATION LIST 80000
HOW MANY LEVELS?
? 3
EVENTS? (LOWEST FIRST) (SINGLE ASSUMED AT TOP)
? 3
? 5
DESTINATION?
 1  1 ? 5
 1  2 ? 5
 1  3 ? 5
 2  1 ? 1
 2  2 ? 1
 2  3 ? 1
 2  4 ? 1
 2  5 ? 1
CONDITIONALS?(0,0=SKIP)
? 0,0
GATE TYPES
 2  5 ? 1
 3  1 ? 1

 2  5  3.34509 -.3544
 3  1  5.22631  5.56665


SYSTEM (ITERATION  1)
ALPHA   BETA   E(P)     E(P*P)    V(P)

   5.2263  5.5667 .486698  .254987  .01811236


 END OF DATA  AT  58
BASIC EXECUTION ERROR

SBU      0.678 UNTS.

RUN COMPLETE.
```


NO PROPERLY ORIENTED THRUSTER AVAILABLE
5.7836
2.1484
1
OPERATIONAL THRUSTER FAILED OR MISORIENTED
5.3457
6.7
11
STANDBY THRUSTER FAILED OR MISORIENTED
5.3457
6.7
11
SECOND RUN
THRUSTER FAILED
3,1
5.2263
5.5667
111
THRUSTER MISORIENTED
3,2
SPURIOUS COMMAND
GIMBAL ASSEMBLY FAILURE
2,1
COMMAND FAILURE
FIRST RUN
MOTOR AND GEARING FAILURE
1,1
14.4370
-.5572
ACTUATOR LINKAGE FAILURE
1,2
14.437
-.5572
LOWER SUPPORT FAILURE
1,3
30.4268
-.6538
UPPER SUPPORT FAILURE
1,4
44.5823
-.6841

```
READY.
90000 DATA 14.437,-.5572,14.437,-.5572,30.4268,-.6538
90002 DT
90002 DATA 44.5823,-.6841,5.2263,5.5667
90004
RUN
PROGRAM   BETFTA

FOR EXPLANATION LIST 80000
HOW MANY LEVELS?
? 4
EVENTS? (LOWEST FIRST) (SINGLE ASSUMED AT TOP)
? 4
? 1
? 2
DESTINATION?
 1   1 ? 1
 1   2 ? 1
 1   3 ? 1
 1   4 ? 1
 2   1 ? 2
 3   1 ? 1
 3   2 ? 1
CONDITIONALS?(0,0=SKIP)
? 0,0
GATE TYPES
 2   1 ? 1
 3   2 ? 1
 4   1 ? 1

 2   1   16.5227   .353853
 3   2   16.5227   .353853
 4   1   5.34573   6.70005


SYSTEM (ITERATION  1)
ALPHA    BETA    E(P)      E(P*P)     V(P)

   5.3457  6.7000 .451789  .220575  .01646148


 END OF DATA  AT  58
BASIC EXECUTION ERROR

SBU       0.717 UNTS.

RUN COMPLETE.
```

FIRST
RUN

```
90000 DATA 5.3457,6.7,5.3457,6.7
90002
90004
RUN

 76/12/14. 15.59.50.
PROGRAM   BETFTA

FOR EXPLANATION LIST 80000
HOW MANY LEVELS?
? 2
EVENTS? (LOWEST FIRST) (SINGLE ASSUMED AT TOP)
? 2
DESTINATION?
 1  1 ? 1
 1  2 ? 1
CONDITIONALS?(0,0=SKIP)
? 0,0
GATE TYPES
 2  1 ? 4

 2  1  5.78357  2.1484


SYSTEM (ITERATION  1)
ALPHA   BETA   E(P)    E(P*P)    V(P)

   5.7836  2.1484 .683004  .486299  .01980519


 END OF DATA  AT  58
BASIC EXECUTION ERROR

SBU      0.681 UNTS.

RUN COMPLETE.
```

6. At this point only series (or gate) relationships remain in the system. Therefore BETAL1 is used to obtain Principal Subsystem Parameter values as well as the system level value of expected reliability and the associated 80%, 90% and 95% Lower Confidence Bounds. (LCB)

In order to illustrate the before-the-fact test planning capability of BETAL1, arbitrary and significantly different test costs have been assigned as shown

1. Redundant Thruster Subsystem (No Properly Oriented Thruster available)

   α = 5.7836

   β = 2.1484

   Test Cost = $50,000 per test

2. Redundant PCC Subsystem (Loss of PCC Function)

   α = 182.2226

   β = -0.859

   Test Cost = $1,000 per test

3. Propellant Containment/Delivery Subsystem (Improper Propellant Flow to Vaporizer)

   α = 93.2741

   β = 1.2352

   Test Cost = $10,000 per test

The program will first display component values if requested (1 = Yes, 0 = No), and then compute the system level expected reliability E(R) and variance V(R) values. A numerical integration follows and the result "Closure" is printed. Since analytic integration would yield a result of 1.0, the closure statement can be used to assess the quality of the numerical approximation and the accuracy of the following results. The 80, 90, 95% lower confidence bounds are then provided.

```
FILE NAME: BETAL1
READY.
RUN

 77/01/27. 19.23.30.
PROGRAM   BETAL1

RUN IN DØUBLE PRECISIØN
PERMIT NEGATIVE BETA?
? 1
TYPE ØF INPUT?
1=PARAMETERS,2=MØMENTS (MEAN & VAR)
? 1
HØW MANY CØMPØNENTS?
? 3
VALUES? (THIRD VALUE IS CØST ØF FIRST TEST)
? 5.7836,2.1484,50000
? 182.2276,-.859,1000
? 93.2741,1.2352,10000
DISPLAY CØMPØNENT VALUES?
? 1

NØ. ALPHA   BETA  E(P)     E(P*P)    V(P)      CØST

  1     5.78  2.15 .683004 .486300 .01980510  50000.00
  2   182.23  -.86 .999231 .998467 .00000417   1000.00
  3    93.27  1.24 .976840 .954448 .00023202  10000.00



FØR SYSTEM


E(R)      E(R*R)      V(R)

.666673    .463436    .01898387


CLØSURE
 .999672
LØWER CØNF. BØUNDS
80  .5480  90  .4780  95  .4210
```

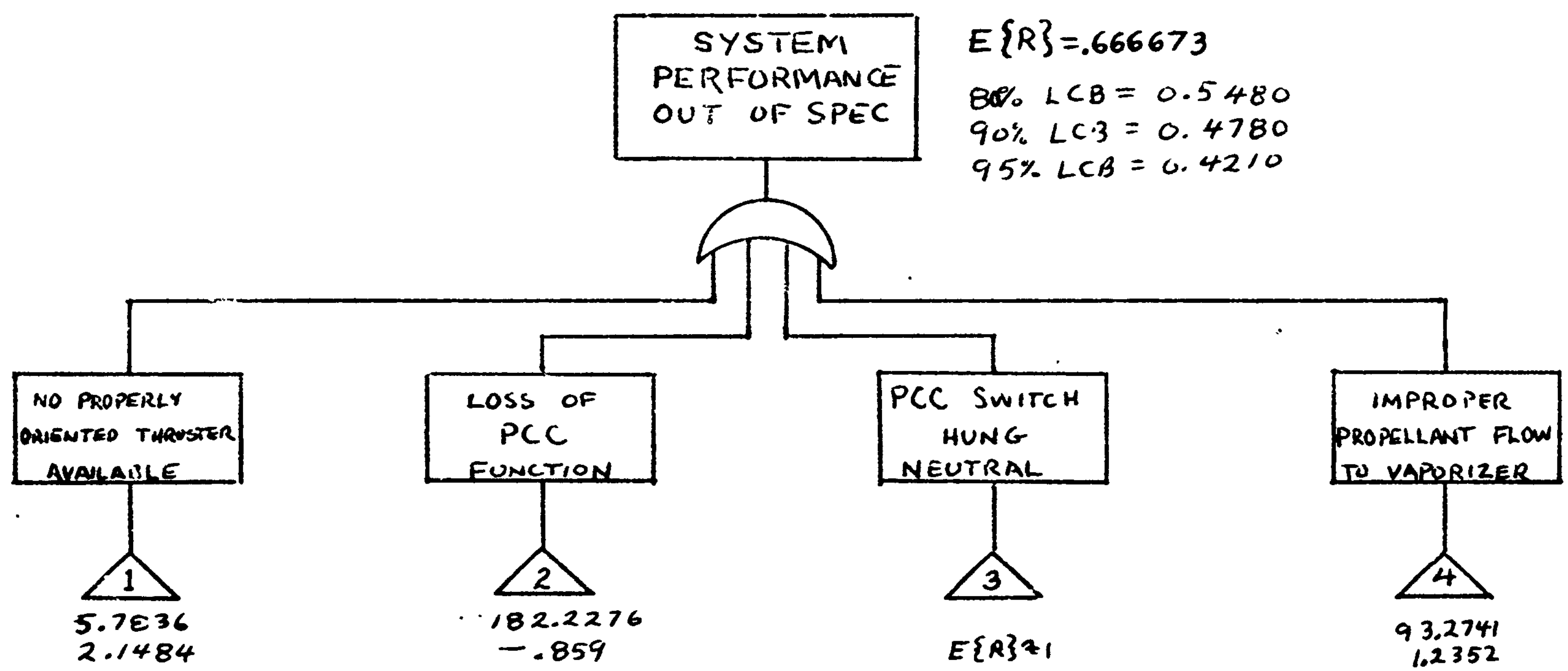
The program then enters the test planning routines using the greatest reduction in uncertainty (variance) per test dollar as the principal criteria in selecting components for testing. As out put the identity of the component tested, the change in variance (DELV), and test cost are provided. In addition a running count of total test cost per component and total number of tests per component are also presented. The system level values of expected reliability and variance are then recomputed. NOte that as expected the expected reliability is the same, but the variance V(R) has decreased. Numerical integration quality is again provided by "Closure" and is followed by the 80, 90, 95 lower confidence bands. These lower bands also reflect the decrease in variance in the increased values of reliability at each bound level. The expected value of variance reduction E(DELVAR) is then provided.

```
FIRST COMPONENT TESTED
NO.    DELV        COST        TOT COST     NO. TESTS

  1 .00000003 *50000.00    50000.00        1


FOR SYSTEM


E(R)      E(R*R)      V(R)

.666673    .461855    .01740208


CLOSURE
 .99963
LOWER CONF. BOUNDS
80  .5530  90  .4870  95  .4320


E(DELVAR)=.00133831
```

The program next asks if a subsequent test is desired (Continue, Yes = 1, No = 0). For this example, two further test sequences were requested. At the end of the second additional sequence, a summary display was requested. In addition to the α, β, and expected reliability E(R) values for each component, the total number of tests and total test dollars per component are provided.

```
CØNTINUE?
? 1
CHANGE NEXT CØST?
? 0

NEW VALUES FØR LAST CØMPØNENT TESTED
NØ. ALPHA    BETA  E(P)     E(P*P)     V(P)       CØST
  1     6.47  2.47 .683004 .484640 .01814527  50000.00

NEXT CØMPØNENT TESTED
NØ.      DELV       CØST      TØT CØST    NØ. TESTS

  1 .00000003 *50000.00  100000.00        2



FØR SYSTEM


E(R)      E(R*R)      V(R)

.666673   .460517    .01606492


CLØSURE
 .999693
LØWER CØNF. BØUNDS
80  .5580  90  .4940  95  .4420



E(DELVAR)=.00114635


CØNTINUE?
? 1
CHANGE NEXT CØST?
? 0

NEW VALUES FØR LAST CØMPØNENT TESTED
NØ. ALPHA    BETA  E(P)     E(P*P)     V(P)       CØST
  1     7.15  2.78 .683004 .483237 .01674214  50000.00
```

```
NEXT CØMPØNENT TESTED
NØ.     DELV        CØST       TØT CØST     NØ. TESTS

  1 .00000002 *50000.00  150000.00        3


FØR SYSTEM


E(R)      E(R*R)      V(R)

.666673   .459372   .01491972


CLØSURE
 .999775
LØWER CØNF. BØUNDS
80  .5620  90  .5010  95  .4510


E(DELVAR)=.00099296


CØNTINUE?
? 0
DISPLAY STATUS FØR ALL CØMPØNENTS?
? 1

NØ.  ALPHA   BETA   E(P)  TESTS   CØST

  1     7.83  3.10 .683004   3  150000.00
  2   182.23  -.86 .999231   0        .00
  3    93.27  1.24 .976840   0        .00


SBU      6.183 UNTS.

RUN CØMPLETE.
```


SYSTEM PERFORMANCE OUT OF SPEC
E{R}=.666673
80% LCB = 0.5480
90% LCB = 0.4780
95% LCB = 0.4210
NO PROPERLY ORIENTED THRUSTER AVAILABLE
1
5.7E36
2.1484
LOSS OF PCC FUNCTION
2
182.2276
-.859
PCC SWITCH HUNG NEUTRAL
3
E{R}≈1
IMPROPER PROPELLANT FLOW TO VAPORIZER
4
93.2741
1.2352

EXAMPLE II CATALYTIC MONOPROPELLANT SYSTEM

1. Mission 5 years or 43,800 hrs

   a. 0.1 lbs Thrusters (Position Control)

      1. Pulse

         a. Cycles = 6348
         b. CUM Firing Time = 1.75 hrs

      2. Steady State

         a. Cycles = 11
         b. CUM Firing Time = 14.55 hrs

   b. 5.0 lbs Thrusters (Δ V)

      1. Pulse

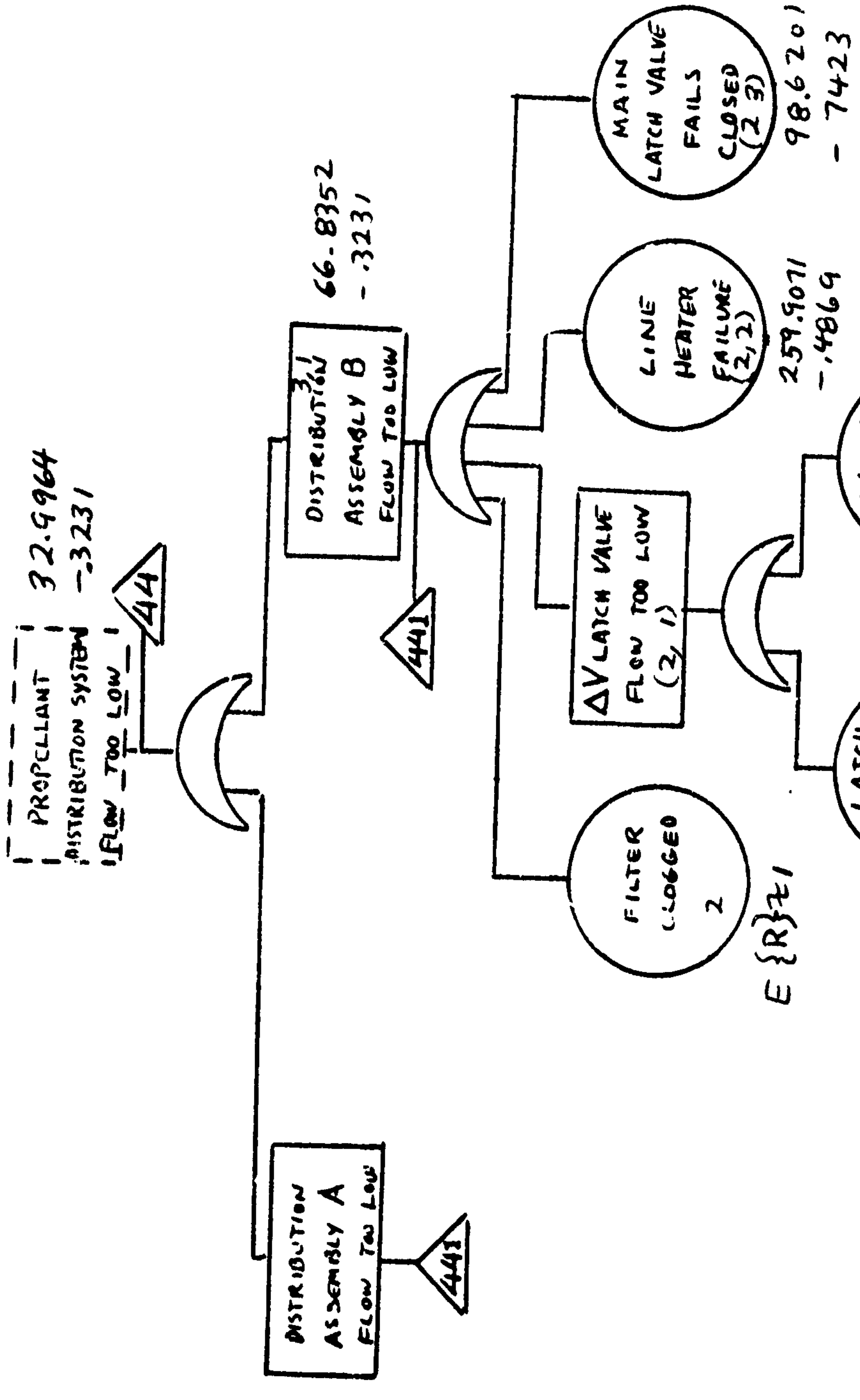
         a. Cycles = 3100
         b. CUM Firing Time = 0.1 hr

      2. Steady State

         a. Cycles = 2
         b. CUM Firing Time = 0.4 hr

2. Evaluation Point, t mission = 5 years; End of Mission

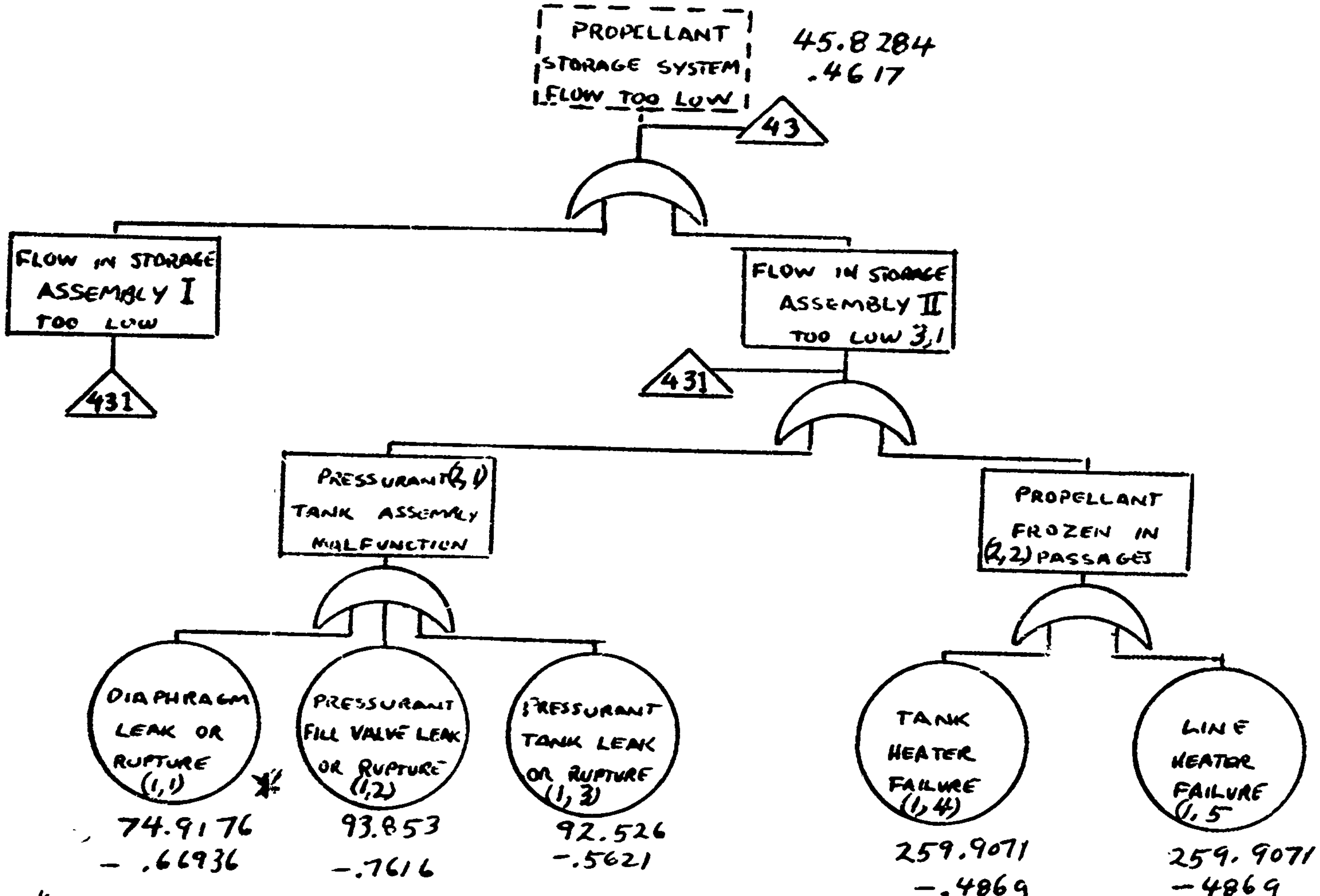
3. Procedure: Because of the more complex tree developed for this system each tree section (still to be treated as entities) will be evaluated completely (using BETFTA and COMP1) before moving to the next section.


PROPELLANT DISTRIBUTION SYSTEM FLOW TOO LOW
32.9964
-.3231
44
DISTRIBUTION ASSEMBLY B FLOW TOO LOW
3.1
66.8352
-.3231
441
DISTRIBUTION ASSEMBLY A FLOW TOO LOW
441
FILTER CLOGGED 2
ΔV LATCH VALVE FLOW TOO LOW (2,1)
LATCH VALVE A FAILS CLOSED (1,1)
93.8553
-.7431
LATCH VALVE B FAILS CLOSED (1,2)
93.8553
-.7431
LINE HEATER FAILURE (2,2)
259.9071
-.4869
MAIN LATCH VALVE FAILS CLOSED (2,3)
98.6201
-.7423

```
PROGRAM   COMP1

OUTPUT FORMAT IS
R.05      R.5       ALPHA       BETA

COMPONENT CODE?(ZZ=END)
? FTC
OPTIME=? (0=END)
? 16.3
  .999997    1.00000     *456219.2871     -.6581
OPTIME=?
? 0

COMPONENT CODE?(ZZ=END)
? ILVC
INPUT OPTION
1=FIXED CYCLES/MISSION HR., 2=SEPARATE
? 2
CYCLES=? (0=END)
? 3102
MISSION TIME =? (0=END)
? 43800
  .985436     .999499      93.8553     -.7431
CYCLES=? (0=END)
? 0

COMPONENT CODE?(ZZ=END)
? HLTV
MISSION TIME=? (0=END)
? 43800
  .992625     .999085     259.9071     -.4869
OPTIME=?
? 0

COMPONENT CODE?(ZZ=END)
? ILVC
INPUT OPTION
1=FIXED CYCLES/MISSION HR., 2=SEPARATE
? 2
CYCLES=? (0=END)
? 1000
MISSION TIME =? (0=END)
? 43800
  .986108     .999518      98.6201     -.7423
CYCLES=? (0=END)
? 0

COMPONENT CODE?(ZZ=END)
? ZZ
NO SUCH COMPONENT

SBU      5.589 UNTS.

RUN COMPLETE.
```

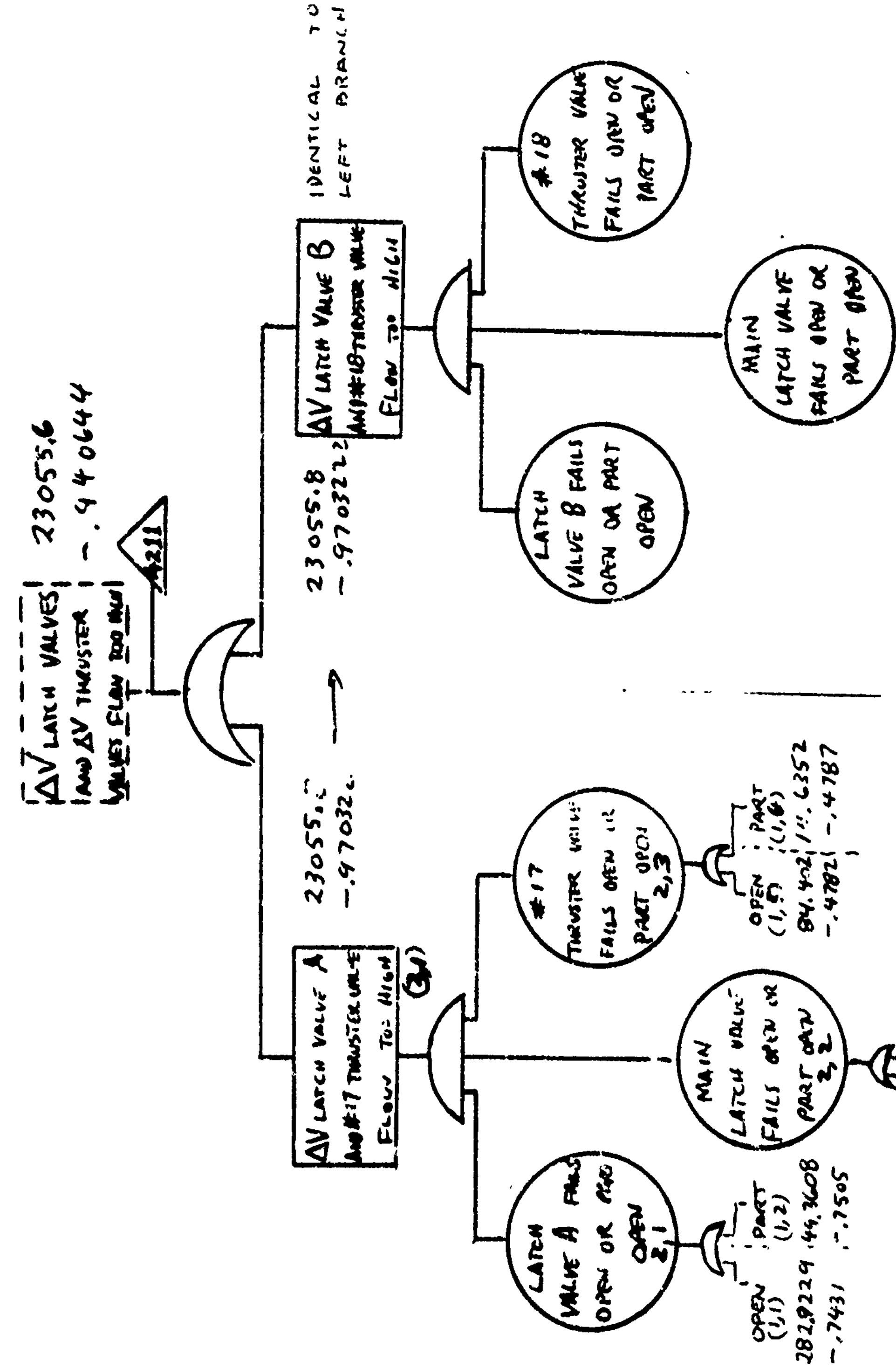
```
BASIC,OLD,BETFTA
READY.
90000 DATA 93.8553,-.7431,93.8553,-.7431
90002 DATA 259.9071,-.4869,98.6201,-.7423
RU N
ILLEGAL COMMAND.
RUN

 76/12/14. 19.22.06.
PROGRAM   BETFTA

FOR EXPLANATION LIST 80000
HOW MANY LEVELS?
? 3
EVENTS? (LOWEST FIRST) (SINGLE ASSUMED AT TOP)
? 2
? 3
DESTINATION?
 1   1 ? 1
 1   2 ? 1
 2   1 ? 1
 2   2 ? 1
 2   3 ? 1
CONDITIONALS?(0,0=SKIP)
? 0,0
GATE TYPES
 2   1 ? 3
 3   1 ? 1

 2   1   46.611   -.743106
 3   1   66.8352 -.323087


SYSTEM (ITERATION  1)
ALPHA    BETA    E(P)      E(P*P)     V(P)

  66.8352  -.3231 .990120  .980478  .00014073


 END OF DATA  AT  58
BASIC EXECUTION ERROR

SBU       0.699 UNTS.

RUN COMPLETE.
```

```
90000 DATA 66.8352,-.3231
90002 DATA 66.8352,-.3231
RUN

 76/12/14. 19.26.16.
PROGRAM   BETPTA

FOR EXPLANATION LIST 80000
HOW MANY LEVELS?
? 2
EVENTS? (LOWEST FIRST) (SINGLE ASSUMED AT TOP)
? 2
DESTINATION?
 1  1 ? 1
 1  2 ? 1
CONDITIONALS?(0,0=SKIP)
? 0,0
GATE TYPES
 2  1 ? 3

 2  1  32.9964 -.323119


SYSTEM (ITERATION  1)
ALPHA   BETA   E(P)     E(P*P)    V(P)

  32.9964  -.3231 .980478  .961874  .00053655


 END OF DATA  AT  58
BASIC EXECUTION ERROR

SBU       0.668 UNTS.

RUN COMPLETE.
```



* INITIAL CALCULATIONS EMPLOYED THE ELASTOMERIC BLADDER/DIAPHRAGM MODEL. BECAUSE OF THE LOW RESULTING RELIABILITY ESTIMATES, THE METALLIC DIAPHRAGM MODEL WAS SUBSTITUTED

```
90000 DATA 74.9176,-.66936,93.853,-.7616,92.526,-.5621
90002 DATA 259.9071,-.4869,259.9071,-.4869
90004 DATA 74.9176,-.66936
90006 DATA 93.853,-.7616,92.526,-.5621
90008 DATA 259.9071,-.4869,259.9071,-.4869
99999 END
READY.
RUN

 76/12/15. 10.21.26.
PROGRAM   BETFTA

FOR EXPLANATION LIST 80000
HOW MANY LEVELS?
? 4
EVENTS? (LOWEST FIRST) (SINGLE ASSUMED AT TOP)
? 10
? 4
? 2
DESTINATION?
 1   1 ? 1
 1   2 ? 1
 1   3 ? 1
 1   4 ? 2
 1   5 ? 2
 1   6 ? 3
 1   7 ? 3
 1   8 ? 3
 1   9 ? 4
 1   10  ? 4
 2   1 ? 1
 2   2 ? 1
 2   3 ? 2
 2   4 ? 2
 3   1 ? 1
 3   2 ? 1
 CONDITIONALS?(0,0=SKIP)
 ? 0,0
 GATE TYPES
  2  1 ? 1
  2  2 ? 3
  2  3 ? 1
  2  4 ? 3
  3  1 ? 1
  3  2 ? 1
  4  1 ? 3

  2  1  84.939   -3.63317E-3
  2  2  129.575  -.486901
  2  3  84.939   -3.63317E-3
  2  4  129.575  -.486901
  3  1  92.8817   .461643
  3  2  9.817   .461643
  4  1  45.8284   .461688


 SYSTEM (ITERATION  1)
 ALPHA   BETA   E(P)      E(P*P)     V(P)

   45.8284   .46.7 .969731  .940974  .00059551
```



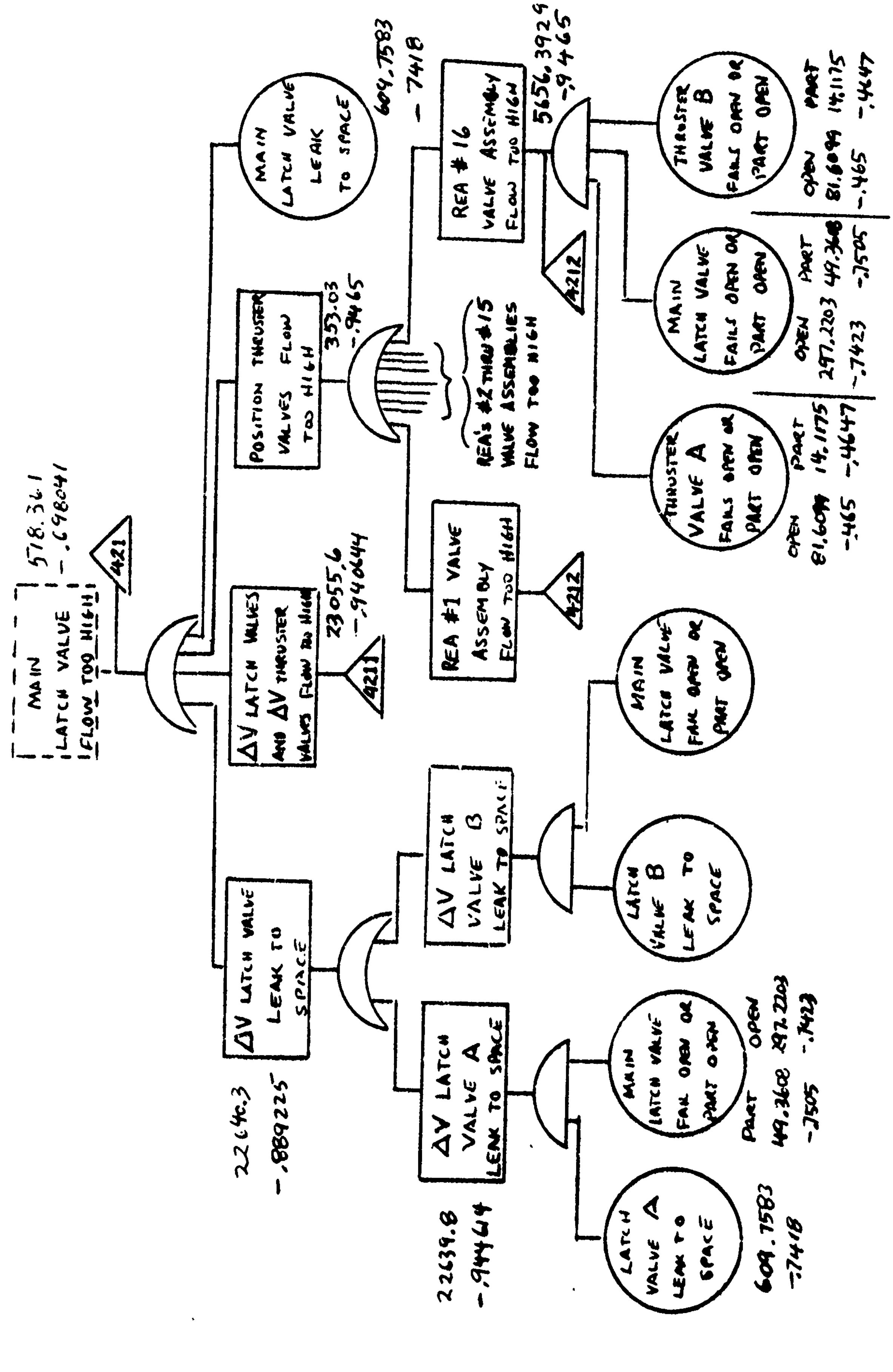
ΔV LATCH VALVES AND ΔV THRUSTER VALVES FLOW TOO HIGH
23055.6
-.440644
A211
23055.8
-.970322
-.970322
ΔV LATCH VALVE A AND #17 THRUSTER VALVE FLOW TOO HIGH
(3,1)
ΔV LATCH VALVE B AND #18 THRUSTER VALVE FLOW TOO HIGH
IDENTICAL TO LEFT BRANCH
LATCH VALVE A FAILS OPEN OR PART OPEN 2,1
MAIN LATCH VALVE FAILS OPEN OR PART OPEN 2,2
#17 THRUSTER VALVE FAILS OPEN OR PART OPEN 2,3
LATCH VALVE B FAILS OPEN OR PART OPEN
MAIN LATCH VALVE FAILS OPEN OR PART OPEN
#18 THRUSTER VALVE FAILS OPEN OR PART OPEN
OPEN (1,1)
2829229
-.7431
PART (1,2)
49.3608
-.7505
OPEN (1,3)
2972203
-.7423
PART (1,4)
49.3608
-.7505
OPEN (1,5)
-.4782
PART (1,6)
-.4787

```
PROGRAM   COMP1

OUTPUT FORMAT IS
R.05      R.5       ALPHA       BETA

COMPONENT CODE?(ZZ=END)
? ILVO
INPUT OPTION
1=FIXED CYCLES/MISSION HR., 2=SEPARATE
? 2
CYCLES=? (0=END)
? 3102
MISSION TIME =? (0=END)
? 43800
  .995122     .999833     282.9229     -.7431
CYCLES=? (0=END)
? 0

COMPONENT CODE?(ZZ=END)
? ILVP
MISSION TIME=? (0=END)
? 43800
  .973039     .999133     49.3608      -.7505
OPTIME=?
? 0

COMPONENT CODE?(ZZ=END)
? EVO
DESIGN CYCLE LIFE,OP. LIFE,MISSION DURATION
? 3102,.5,43800
INPUT OPTION
1=FIXED CYCLES/OP.HR.,2=SEPARATE
? 2
CYCLES=? (0=END)
? 3102
MISSION TIME,OP. TIME (0,0=END9
? 43800,.5
  .977400     .997116     84.4020      -.4782
CYCLES=? (0=END)
? 0
```

```
COMPONENT CODE?(ZZ=END)
? EVP
DESIGN CYCLE LIFE, OP. LIFE, MISSION DURATION
? 3102,.5,43800
INPUT OPTION
1=FIXED CYCLES/OP.HR.,2=SEPARATE
? 2
CYCLES=? (0=END)
? 3102
MISSION TIME,OP. TIME (0,0=END9
? 43800,.5
  .881509      .984209      14.6352      -.4787
CYCLES=? (0=END)
? 0

COMPONENT CODE?(ZZ=END)
? ILVO
INPUT OPTION
1=FIXED CYCLES/MISSION HR., 2=SEPARATE
? 2
CYCLES=? (0=END)
? 1000
MISSION TIME =? (0=END)
? 43800
  .995348      .999839      297.2203     -.7423
CYCLES=? (0=END)
? 0

COMPONENT CODE?(ZZ=END)
? ILVP
MISSION TIME=? (0=END)
? 43800
  .973039      .999133      49.3608      -.7505
OPTIME=?
? 0

COMPONENT CODE?(ZZ=END)
? ZZ
NO SUCH COMPONENT

SBU      5.717 UNTS.

RUN COMPLETE.
```

```
PROGRAM   BETFTA

90000 DATA 282.9229,-.7431,49.36,-.7505
90002 DATA 297.2203,-.7423,49.3608,-.7505
90004 DATA 84.402,-.4782,14.6352,-.4787
99999 END
READY.
RUN

 76/12/14. 19.58.13.
PROGRAM   BETFTA

FOR EXPLANATION LIST 80000
HOW MANY LEVELS?
? 3
EVENTS? (LOWEST FIRST) (SINGLE ASSUMED AT TOP)
? 6
? 3
DESTINATION?
 1   1 ? 1
 1   2 ? 1
 1   3 ? 2
 1   4 ? 2
 1   5 ? 3
 1   6 ? 3
 2   1 ? 1
 2   2 ? 1
 2   3 ? 1
CONDITIONALS?(0,0=SKIP)
? 0,0
GATE TYPES
 1   1 ? 1
 2   2 ? 1
 2   3 ? 1
 3   1 ? 2

 2   1   56.7885 -.661149
 2   2   56.5515 -.664897
 2   3   16.9787 -.287052
 3   1   23055.8 -.970322


SYSTEM (ITERATION  1)
ALPHA    BETA    E(P)      E(P*P)     V(P)

*23055.7676  -.9703 .999999  .999997  .00000000


 END OF DATA  AT  58
BASIC EXECUTION ERROR

SBU       0.740 UNTS.

RUN COMPLETE.
```

```
90000 DATA 23055.8,-.970322,23055.8,-.970322
90002
90004
90006
LIST,90000

 76/12/14. 20.02.03.
PROGRAM   BETFTA

90000 DATA 23055.8,-.970322,23055.8,-.970322
99999 END
READY.
RUN

 76/12/14. 20.02.19.
PROGRAM   BETFTA

FOR EXPLANATION LIST 80000
HOW MANY LEVELS?
? 2
EVENTS? (LOWEST FIRST) (SINGLE ASSUMED AT TOP)
? 2
DESTINATION?
 1  1 ? 1
 1  2 ? 1
CONDITIONALS?(0,0=SKIP)
? 0,0
GATE TYPES
 2  1 ? 1

 2  1  23055.6 -.940644


SYSTEM (ITERATION  1)
ALPHA   BETA   E(P)     E(P*P)    V(P)

*23055.6117  -.9406 .999997  .999995  .00000000


 END OF DATA  AT  58
BASIC EXECUTION ERROR

SBU      0.681 UNTS.

RUN COMPLETE.
```


MAIN LATCH VALVE FLOW TOO HIGH
578.361
-.698041
421
ΔV LATCH VALVES AND ΔV THRUSTER VALVES FLOW TOO HIGH
23055.6
-.940644
421
POSITION THRUSTER VALVES FLOW TOO HIGH
353.03
-.9465
MAIN LATCH VALVE LEAK TO SPACE
609.7583
-.7418
REA #16 VALVE ASSEMBLY FLOW TOO HIGH
5656.3929
-.9465
212
REA's #2 THRU #15 VALVE ASSEMBLIES FLOW TOO HIGH
REA #1 VALVE ASSEMBLY FLOW TOO HIGH
212
THRUSTER VALVE A FAILS OPEN OR PART OPEN
OPEN 81.6099 -.465
PART 14.1175 -.4647
MAIN LATCH VALVE FAILS OPEN OR PART OPEN
OPEN 297.2203 -.7423
PART 49.3608 -.7505
THRUSTER VALVE B FAILS OPEN OR PART OPEN
OPEN 81.6099 -.465
PART 14.1175 -.4647
ΔV LATCH VALVE LEAK TO SPACE
22640.3
-.889225
ΔV LATCH VALVE B LEAK TO SPACE
LATCH VALVE B LEAK TO SPACE
MAIN LATCH VALVE FAIL OPEN OR PART OPEN
ΔV LATCH VALVE A LEAK TO SPACE
22639.8
-.944614
MAIN LATCH VALVE FAIL OPEN OR PART OPEN
PART 49.3608 -.7505
OPEN 297.2203 -.7423
LATCH VALVE A LEAK TO SPACE
609.7583
-.7418

```
PROGRAM   COMP1

OUTPUT FORMAT IS
R.05      R.5       ALPHA      BETA

COMPONENT CODE?(ZZ=END)
? ILVL
MISSION TIME=? (0=END)
? 43800
  .997725     .999921     609.7583     -.7418
OPTIME=?
? 0

COMPONENT CODE?(ZZ=END)
? ILVO
INPUT OPTION
1=FIXED CYCLES/MISSION HR., 2=SEPARATE
? 2
CYCLES=? (0=END)
? 1000
MISSION TIME =? (0=END)
? 43800
  .995348     .999839     297.2203     -.7423
CYCLES=? (0=END)
? 0

COMPONENT CODE?(ZZ=END)
? ILVP
MISSION TIME=? (0=END)
? 43800
  .973039     .999133      49.3608     -.7505
OPTIME=?
? .05
 1.00000     1.00000     *43832710.7167     -.7505
OPTIME=?
? 0

COMPONENT CODE?(ZZ=END)
? ZZ
NO SUCH COMPONENT

SBU      5.504 UNTS.

RUN COMPLETE.
```

```
PROGRAM   BETFTA

90000 DATA  49.3608,-.7505
90002 DATA 2?/.2203,-.7423
90004 DATA 609.7583,-.7418
99999 END
READY.
RUN

 76/12/14. 20.11.57.
PROGRAM   BETFTA

FOR EXPLANATION LIST 80000
HOW MANY LEVELS?
? 3
EVENTS? (LOWEST FIRST) (SINGLE ASSUMED AT TOP)
? 2
? 2
DESTINATION?
 1   1 ? 2
 1   2 ? 2
 2   1 ? 1
 2   2 ? 1
CONDITIONALS?(0,0=SKIP)
? 0,0
GATE TYPES
 2   2 ? 1
 3   1 ? 2

 2   2   56.5515 -.664897
 3   1   22639.8 -.944614


SYSTEM (ITERATION  1)
ALPHA    BETA    E(P)      E(P*P)     V(P)

*22639.8109   -.9446 .999998   .999995   .00000000


 END OF DATA  AT   58
BASIC EXECUTION ERROR

SBU       0.684 UNTS.

RUN COMPLETE.
```

```
90000 DATA 22639.8,-.944614,22639.8,-.944614
99999 END
READY.
RUN

 76/12/14. 20.15.01.
PROGRAM   BETFTA

FOR EXPLANATION LIST 80000
HOW MANY LEVELS?
? 2
EVENTS? (LOWEST FIRST) (SINGLE ASSUMED AT TOP)
? 2
DESTINATION?
 1   1 ? 1
 1   2 ? 1
CONDITIONALS?(0,0=SKIP)
? 0,0
GATE TYPES
 2   1 ? 1

 2   1   22640.3 -.889225


SYSTEM (ITERATION  1)
ALPHA     BETA    E(P)      E(P*P)     V(P)

*22640.3107   -.8892 .999995  .999990  .00000000


 END OF DATA  AT  56
BASIC EXECUTION ERROR

SBU       0.665 UNTS.

RUN COMPLETE.
```

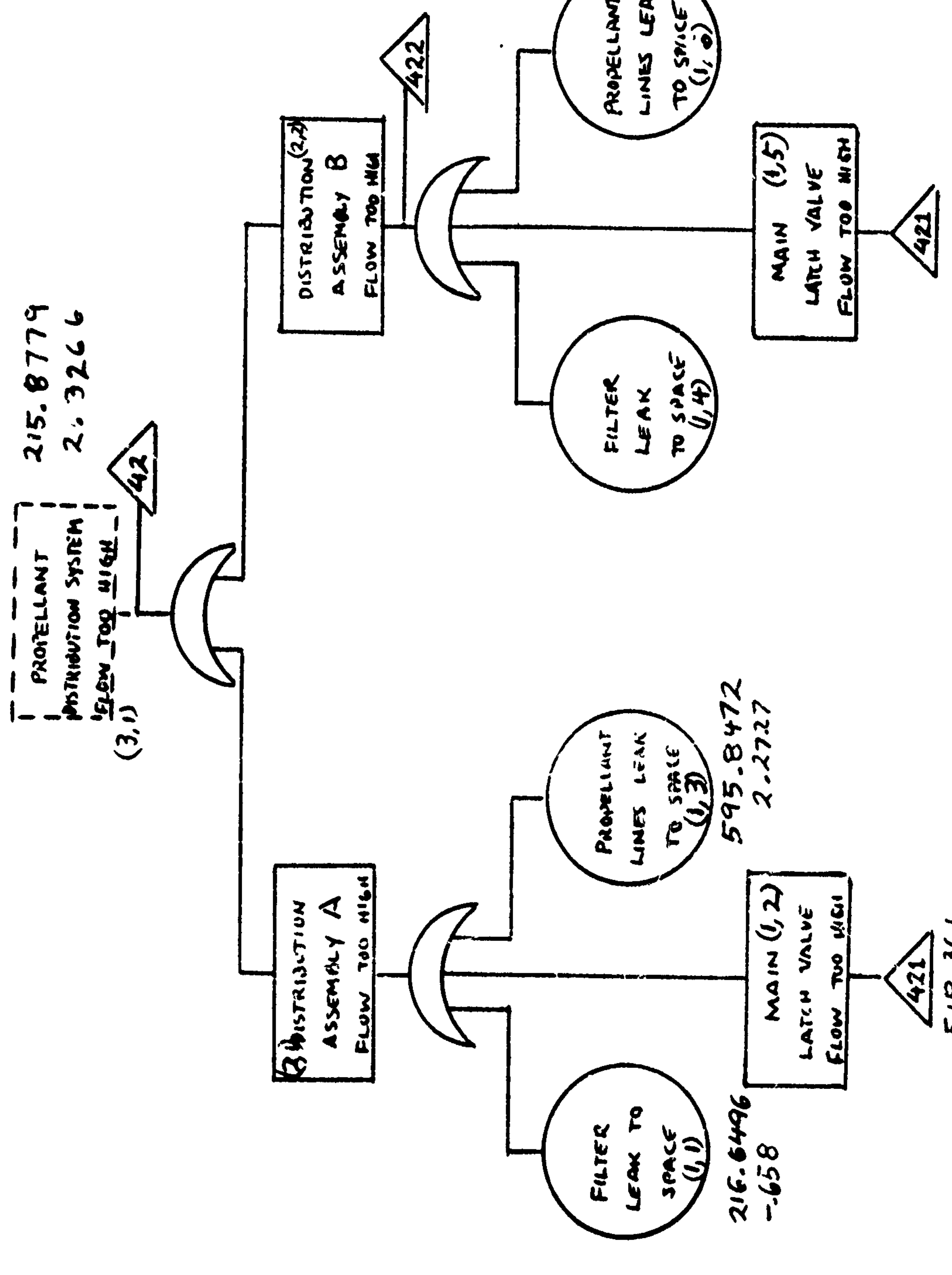
```
PROGRAM   COMP1

OUTPUT FORMAT IS
R.05      R.5       ALPHA       BETA

COMPONENT CODE?(ZZ=END)
? EVO
DESIGN CYCLE LIFE,OP. LIFE,MISSION DURATION
? 6359,16.3,43800
INPUT OPTION
1=FIXED CYCLES/OP.HR.,2=SEPARATE
? 2
CYCLES=? (0=END)
? 6359
MISSION TIME,OP. TIME (0,0=END9
? 43800,16.3
  .976315     .996878      81.6099     -.4650
CYCLES=? (0=END)
? 0

COMPONENT CODE?(ZZ=END)
? EVP
DESIGN CYCLE LIFE, OP. LIFE, MISSION DURATION
? 6359,16.3,43800
INPUT OPTION
1=FIXED CYCLES/OP.HR.,2=SEPARATE
? 2
CYCLES=? (0=END)
? 6339
MISSION TIME,OP. TIME (0,0=END9
? 43800,16.3
  .875973     .982863      14.1175     -.4647
CYCLES=? (0=END)
? 0

COMPONENT CODE?(ZZ=END)
? ILVO
INPUT OPTION
1=FIXED CYCLES/MISSION HR., 2=SEPARATE
? 2
CYCLES=? (0=END)
? 1000
MISSION TIME =? (0=END)
? 43800
  .995348     .999839      297.2203    -.7423
CYCLES=? (0=END)
? 0

COMPONENT CODE?(ZZ=END)
? ILVP
MISSION TIME=? (0=END)
? 43800
  .973039     .999133      49.3608     -.7505
OPTIME=?
? 0
```

```
PRØGRAM   BETFTA

90000 DATA 81.6099,-.465,14.1175,-.4647
90002 DATA 297.2203,-.7423,49.3608,-.7505
90004 DATA 81.6099,-.465,14.1175,-.4647
99999 END
READY.
RUN

 76/12/14. 20.27.10.
PRØGRAM   BETFTA

FØR EXPLANATIØN LIST 80000
HØW MANY LEVELS?
? 3
EVENTS? (LØWEST FIRST) (SINGLE ASSUMED AT TØP)
? 6
? 3
DESTINATIØN?
 1   1 ? 1
 1   2 ? 1
 1   3 ? 2
 1   4 ? 2
 1   5 ? 3
 1   6 ? 3
 2   1 ? 1
 2   2 ? 1
 2   3 ? 1
CONDITIØNALS?(0,0=SKIP)
? 0,0
GATE TYPES
 2   1 ? 1
 2   2 ? 1
 2   3 ? 1
 3   1 ? 2

 2   1   16.3811 -.267999
 2   2   56.5515 -.664897
 2   3   16.3811 -.267999
 3   1   5656.39 -.946512


SYSTEM (ITERATIØN  1)
ALPHA    BETA    E(P)      E(P*P)     V(P)

5656.3929  -.9465 .999991  .999981  .00000000


 END ØF DATA  AT  58
BASIC EXECUTIØN ERRØR

SBU      0.744 UNTS.

RUN COMPLETE.
```

```
PROGRAM   BETFTA

90000 DATA 5656.3929,-.9465
90002 DATA 5656.3929,-.9465
90004 DATA 5656.3929,-.9465
90006 DATA 5656.3929,-.9465
90008 DATA 5656.3929,-.9465
90010 DATA 5656.3929,-.9465
90012 DATA 5656.3929,-.9465
90014 DATA 5656.3929,-.9465
90016 DATA 5656.3929,-.9465
90018 DATA 5656.3929,-.9465
90020 DATA 5656.3929,-.9465
90022 DATA 5656.3929,-.9465
90024 DATA 5656.3929,-.9465
90026 DATA 5656.3929,-.9465
90028 DATA 5656.3929,-.9465
90030 DATA 5656.3929,-.9465
90032LIW
99999 END
READY.
90032
RUN

 76/12/14. 20.36.15.
PROGRAM   BETFTA

FOR EXPLANATION LIST 80000
HOW MANY LEVELS?
? 2
EVENTS? (LOWEST FIRST) (SINGLE ASSUMED AT TOP)
? 16
DESTINATION?
 1   1 ? 1
 1   2 ? 1
 1   3 ? 1
 1   4 ? 1
 1   5 ? 1
 1   6 ? 1
 1   7 ? 1
 1   8 ? 1
 1   9 ? 1
 1   10   ? 1
 1   11   ? 1
 1   12   ? 1
 1   13   ? 1
 1   14   ? 1
 1   15   ? 1
 1   16   ? 1
```

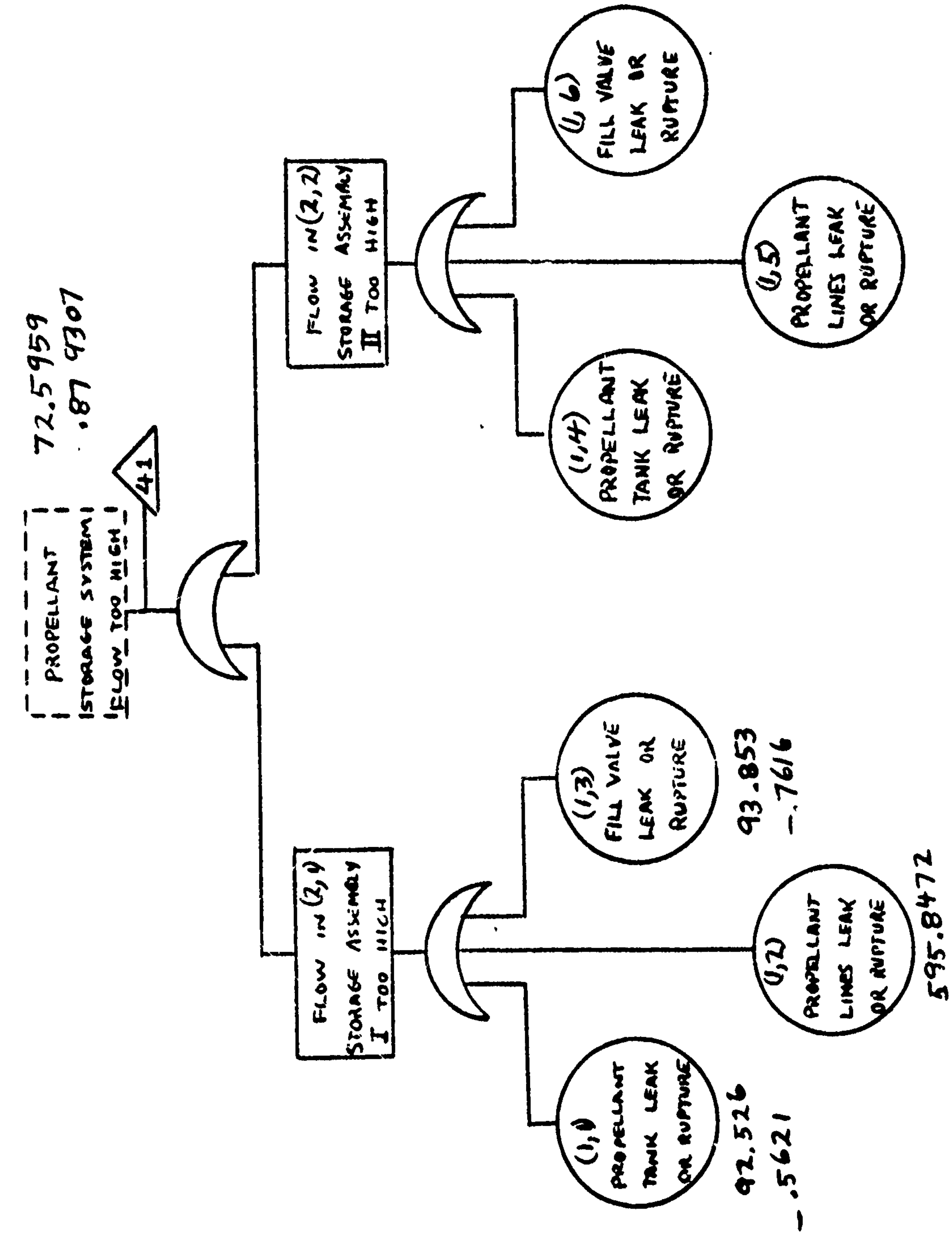
```
CONDITIONALS?(0,0=SKIP)
? 0,0
GATE TYPES
 2  1 ? 3

 2  1  353.03  -.9465


SYSTEM (ITERATION  1)
ALPHA   BETA   E(P)      E(P*P)    V(P)

 353.0303  -.9465 .99[illegible]  .999698  .00000043


PROGRAM   COMP1

OUTPUT FORMAT IS
R.05     R.5      ALPHA      BETA

COMPONENT CODE?(ZZ=END)
? IL VL
 SUBSCRIPT ERROR  AT  209
BASIC EXECUTION ERROR

SBU      5.498 UNTS.

RUN COMPLETE.
RUN

 76/12/14. 20.42.40.
PROGRAM   COMP1

OUTPUT FORMAT IS
R.05     R.5      ALPHA      BETA

COMPONENT CODE?(ZZ=END)
? ILVL
MISSION TIME=? (0=END)
? 43800
  .997725     .999921     609.7583     -.7418
OPTIME=?
? 0

COMPONENT CODE?(ZZ=END)
? ZZ
NO SUCH COMPONENT

SBU      5.594 UNTS.

RUN COMPLETE.
```

```
PROGRAM   BETFTA

90000 DATA 22640.3,-.889225
90002 DATA 23055.6,-.940644
90004 DATA 353.03,-.9465
90006 DATA 609.7583,-.7418
99999 END
READY.
RUN

 76/12/14. 20.47.22.
PROGRAM   BETFTA

FOR EXPLANATION LIST 80000
HOW MANY LEVELS?
? 2
EVENTS? (LOWEST FIRST) (SINGLE ASSUMED AT TOP)
? 4
DESTINATION?
 1  1 ? 1
 1  2 ? 1
 1  3 ? 1
 1  4 ? 1
CONDITIONALS?(0,0=SKIP)
? 0,0
GATE TYPES
 2  1 ? 1

 2  1  518.361 -.698041


SYSTEM (ITERATION  1)
ALPHA    BETA    E(P)      E(P*P)     V(P)

 518.3606  -.6980 .999419  .998839  .00000112


 END OF DATA  AT  58
BASIC EXECUTION ERROR

SBU      0.684 UNTS.

RUN COMPLETE.
```


PROPELLANT DISTRIBUTION SYSTEM FLOW TOO HIGH (3,1)
42
215.8779
2.3266
DISTRIBUTION ASSEMBLY A FLOW TOO HIGH (2,1)
DISTRIBUTION ASSEMBLY B FLOW TOO HIGH (2,2)
422
FILTER LEAK TO SPACE (1,1)
216.6496
-.658
MAIN (1,2) LATCH VALVE FLOW TOO HIGH
421
518.361
-.698041
PROPELLANT LINES LEAK TO SPACE (1,3)
595.8472
2.2727
FILTER LEAK TO SPACE (1,4)
MAIN (1,5) LATCH VALVE FLOW TOO HIGH
421
PROPELLANT LINES LEAK TO SPACE (1,6)

```
PROGRAM   COMP1

OUTPUT FORMAT IS
R.05      R.5       ALPHA       BETA

COMPONENT CODE?(ZZ=END)
? FTL
MISSION TIME=? (0=END)
? 43800
  .992756     .999531     216.6496      -.6580
OPTIME=?
? 0

COMPONENT CODE?(ZZ=END)
? FL
OPTIME=? (0=END)
? 17
  .999997     .999999     *1536763.1884     2.2724
OPTIME=?
? 43800
  .991278     .996699     595.8472     2.2727
OPTIME=?
? 0

COMPONENT CODE?(ZZ=END)
? ZZ
NO SUCH COMPONENT

SBU       5.592 UNTS.
```

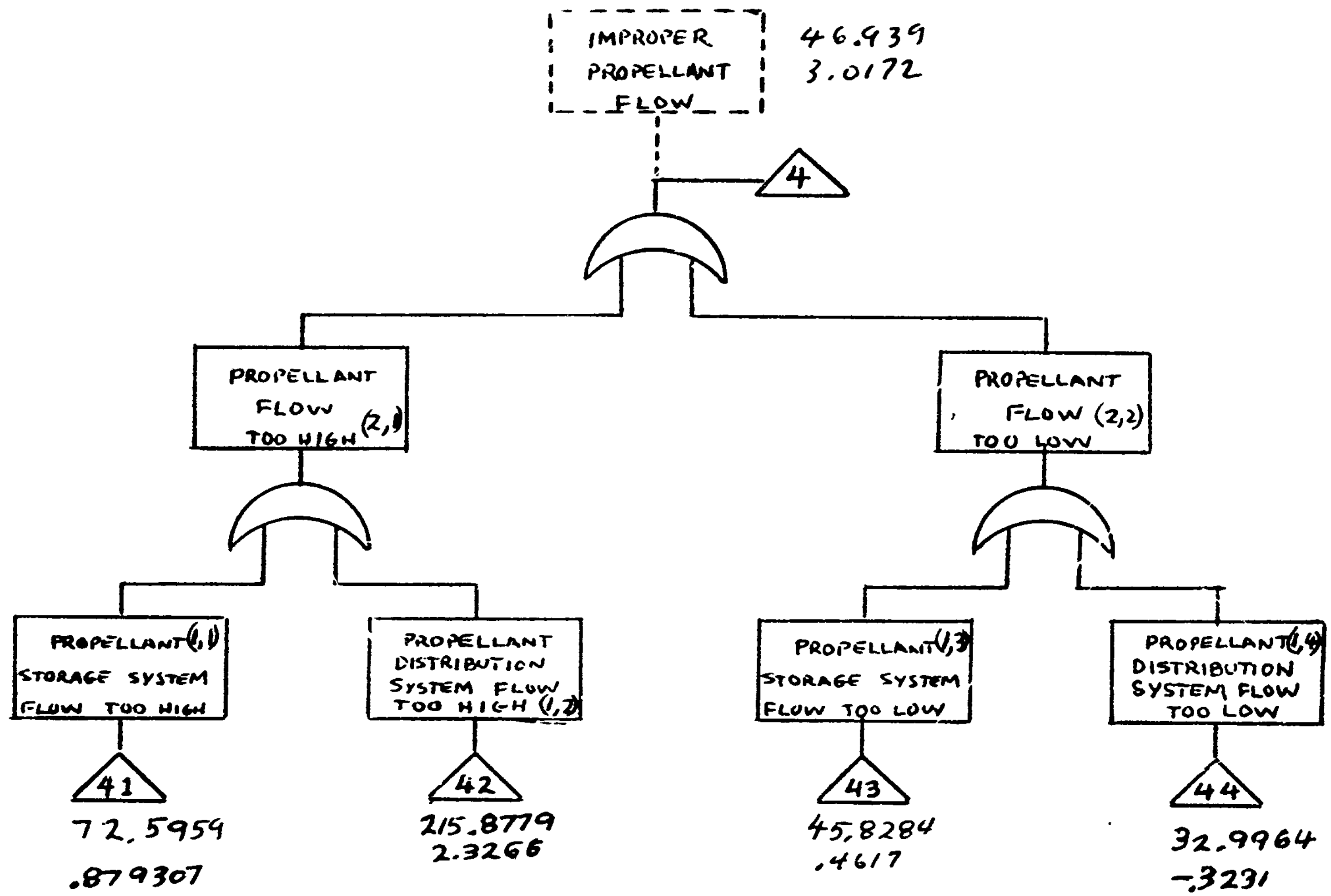
```
PROGRAM   BETFTA

90000 DATA 216.6496,-.658
90002 DATA 518.361,-.698041
90004 DATA 595.8472,2.2727
90006 DATA 216.6496,-.658
90008 DATA 518.361,-.698041
90010 DATA 595.8472,2.2727
99999 END
READY.
RUN

 76/12/14. 21.44.06.
PROGRAM   BETFTA

FOR EXPLANATION LIST 80000
HOW MANY LEVELS?
? 3
EVENTS? (LOWEST FIRST) (SINGLE ASSUMED AT TOP)
? 6
? 2
DESTINATION?
 1  1 ? 1
 1  2 ? 1
 1  3 ? 1
 1  4 ? 2
 1  5 ? 2
 1  6 ? 2
 2  1 ? 1
 2  2 ? 1
CONDITIONALS?(0,0=SKIP)
? 0,0
GATE TYPES
 2  1 ? 1
 2  2 ? 1
 3  1 ? 3

 2  1  433.908  2.32651
 2  2  433.908  2.32651
 3  1  215.878  2.32655


 SYSTEM (ITERATION  1)
 ALPHA   BETA   E(P)     E(P*P)    V(P)

  215.8779  2.3266 .984893  .970082  .00006726


  END OF DATA  AT  58
 BASIC EXECUTION ERROR

 SBU      0.710 UNTS.

 RUN COMPLETE.
```



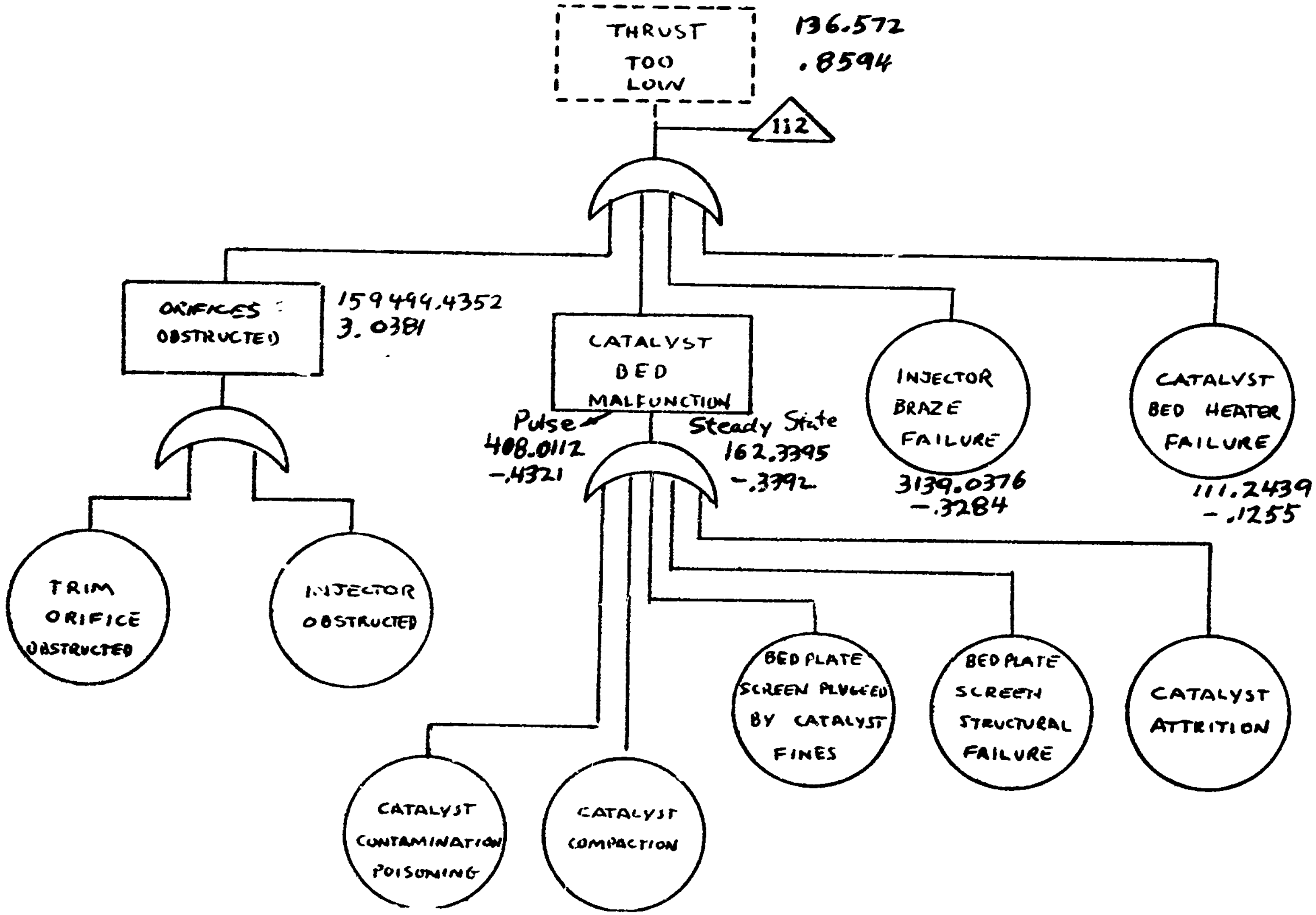
PROPELLANT STORAGE SYSTEM FLOW TOO HIGH
41
72.5959
.87 9307
FLOW IN (2,1) STORAGE ASSEMBLY I TOO HIGH
FLOW IN (2,2) STORAGE ASSEMBLY II TOO HIGH
(1,1) PROPELLANT TANK LEAK OR RUPTURE
92.526
-.5621
(1,2) PROPELLANT LINES LEAK OR RUPTURE
595.8472
2.2727
(1,3) FILL VALVE LEAK OR RUPTURE
93.853
-.7616
(1,4) PROPELLANT TANK LEAK OR RUPTURE
(1,5) PROPELLANT LINES LEAK OR RUPTURE
(1,6) FILL VALVE LEAK OR RUPTURE

```
PRØGRAM   CØMP1

ØUTPUT FØRMAT IS
R.05      R.5       ALPHA       BETA

CØMPØNENT CØDE?(ZZ=END)
? PR
PRESS. TIME=? (0=END)
? 43800
  .981127     .998118      92.5260      -.5621
PRESS. TIME=?
? 0

CØMPØNENT CØDE?(ZZ=END)
? FL
ØPTIME=? (0=END)
? 438000ØHJ
 TØØ MUCH DATA, RETYPE INPUT  AT  2002
? 43800
  .991278     .996699     595.8472      2.2727
ØPTIME=?
? 0

CØMPØNENT CØDE?(ZZ=END)
? FV1
PRESS. TIME=? (0=END)
? 43800
  .985952     .999601      93.8530      -.7616
PRESS. TIME=?
? 0

CØMPØNENT CØDE?(ZZ=END)
? ZZ
NØ SUCH CØMPØNENT

SBU      5.540 UNTS.

RUN CØMPLETE.
```

```
PRØGRAM   BETFTA

90000 DATA 92.526,-.5621
90002 DATA 595.8472,2.2727
90004 DATA 93.853,-.7616
90006 DATA 92.526,-.5621
90008 DATA 595.8472,2.2727
90010 DATA 93.853,-.7616
99999 END
READY.
RUN

 76/12/14. 21.52.01.
PRØGRAM   BETFTA

FØR EXPLANATIØN LIST 80000
HØW MANY LEVELS?
? 3
EVENTS? (LØWEST FIRST) (SINGLE ASSUMED AT TØP)
? 6
? 2
DESTINATIØN?
 1  1 ? 1
 1  2 ? 1
 1  3 ? 1
 1  4 ? 2
 1  5 ? 2
 1  6 ? 2
 2  1 ? 1
 2  2 ? 1
CØNDITIØNALS?(0,0=SKIP)
? 0,0
GATE TYPES
 2  1 ? 1
 2  2 ? 1
 3  1 ? 3

 2  1  146.623   .879254
 2  2  146.623   .879254
 3  1  72.5959   .879307


SYSTEM (ITERATIØN  1)
ALPHA    BETA    E(P)      E(P*P)     V(P)

  72.5959    .8793 .975100  .951138  .00031748


 END ØF DATA  AT  58
BASIC EXECUTIØN ERRØR

SBU       0.715 UNTS.

RUN CØMPLETE.
```


IMPROPER PROPELLANT FLOW
46.939
3.0172
4
PROPELLANT FLOW TOO HIGH (2,1)
PROPELLANT FLOW (2,2) TOO LOW
PROPELLANT (1,1) STORAGE SYSTEM FLOW TOO HIGH
41
72.5959
.879307
PROPELLANT DISTRIBUTION SYSTEM FLOW TOO HIGH (1,2)
42
215.8779
2.3266
PROPELLANT (1,3) STORAGE SYSTEM FLOW TOO LOW
43
45.8284
.4617
PROPELLANT (1,4) DISTRIBUTION SYSTEM FLOW TOO LOW
44
32.9964
-.3231

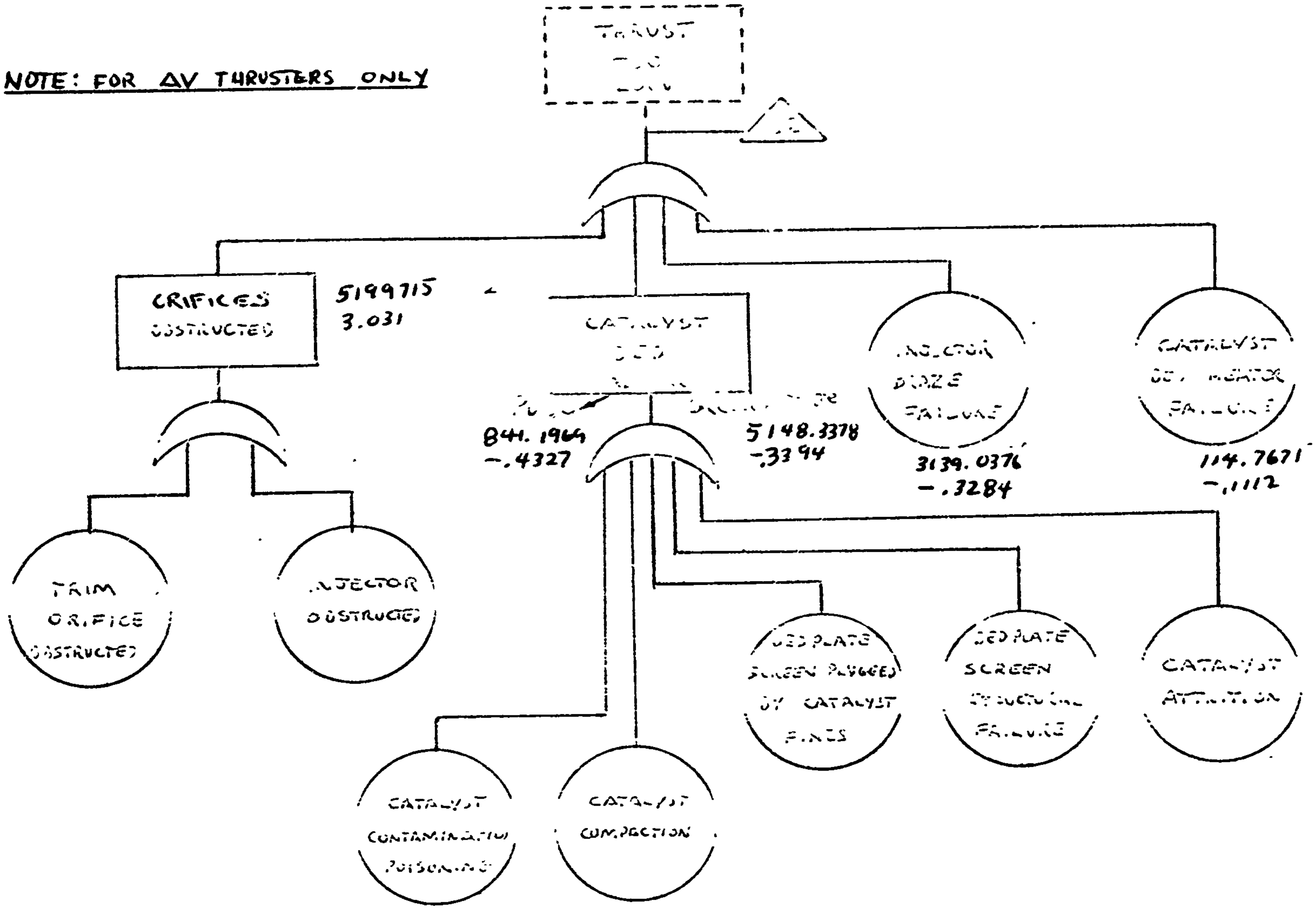
```
PRØGRAM   BETFTA

90000 DATA 72.5959,.879307,215.8779,2.3266,45.8284,.4617
90002 DATA 32.9964,-.3231
99999 END
READY.
RUN

 76/12/15. 10.40.17.
PRØGRAM   BETFTA

FØR EXPLANATIØN LIST 80000
HØW MANY LEVELS?
? 3
EVENTS? (LØWEST FIRST) (SINGLE ASSUMED AT TØP)
? 4
? 2
DESTINATIØN?
 1   1  ? 1
 1   2  ? 1
 1   3  ? 2
 1   4  ? 2
 2   1  ? 1
 2   2  ? 1
CØNDITIØNALS?(0,0=SKIP)
? 0,0
GATE TYPES
 2   1  ? 1
 2   2  ? 1
 3   1  ? 3

 2   1   96.3122   3.01566
 2   2   39.3327   1.08707
 3   1   46.939    3.01716


SYSTEM (ITERATIØN  1)
ALPHA    BETA    E(P)      E(P*P)     V(P)

  46.9390  3.0172 .922682  .852689  .00134716


 END ØF DATA  AT  58
BASIC EXECUTIØN ERRØR

SBU      0.709 UNTS.

RUN CØMPLETE.
```


THRUST TOO LOW
136.572
.8594
112
ORIFICES OBSTRUCTED
159494.4352
3.0381
CATALYST BED MALFUNCTION
Pulse
408.0112
-.4321
Steady State
162.3395
-.3392
INJECTOR BRAZE FAILURE
3139.0376
-.3284
CATALYST BED HEATER FAILURE
111.2439
-.1255
TRIM ORIFICE OBSTRUCTED
INJECTOR OBSTRUCTED
BED PLATE SCREEN PLUGGED BY CATALYST FINES
BED PLATE SCREEN STRUCTURAL FAILURE
CATALYST ATTRITION
CATALYST CONTAMINATION POISONING
CATALYST COMPACTION

```
PROGRAM   COMP1

OUTPUT FORMAT IS
R.05      R.5       ALPHA       BETA

COMPONENT CODE?(ZZ=END)
? IMP
DESIGN OP. LIFE=?
? 16.3
OPTIME=? (0=END)
? 16.3
  .999960      .999983     *159499.4352      3.0381
OPTIME=?
? 0

COMPONENT CODE?(ZZ=END)
? IBF
SAME AS ISL
MISSION TIME=? (0=END)
? 43800
  .999278      .999879     3139.0376      -.3284
OPTIME=?
? 0

COMPONENT CODE?(ZZ=END)
? HET
THRUSTER CYCLES & OP.TIME
 INPUT OPTION
1=FIXED CYCLES/OP.HR., 2=SEPARATE
? 2
CYCLES=? (0=END)
? 6359
OPTIME=? (0=END)
? 16.3
  .976124      .994929      111.2439      -.1255
CYCLES=? (0=END)
? 0

COMPONENT CODE?(ZZ=END)
? CBP
DESIGN CYCLE LIFE,COLD START LIFE,OP.LIFE?
? 6348,1E-6,1.75
CYCLES,COLD STARTS,OP. TIME, (T=0=END)
? 6348,1E-6,1.75
  .995008      .999299      408.0112      -.4321
CYCLES,COLD STARTS,OP. TIME, (T=0=END)
? 0,0,0
```

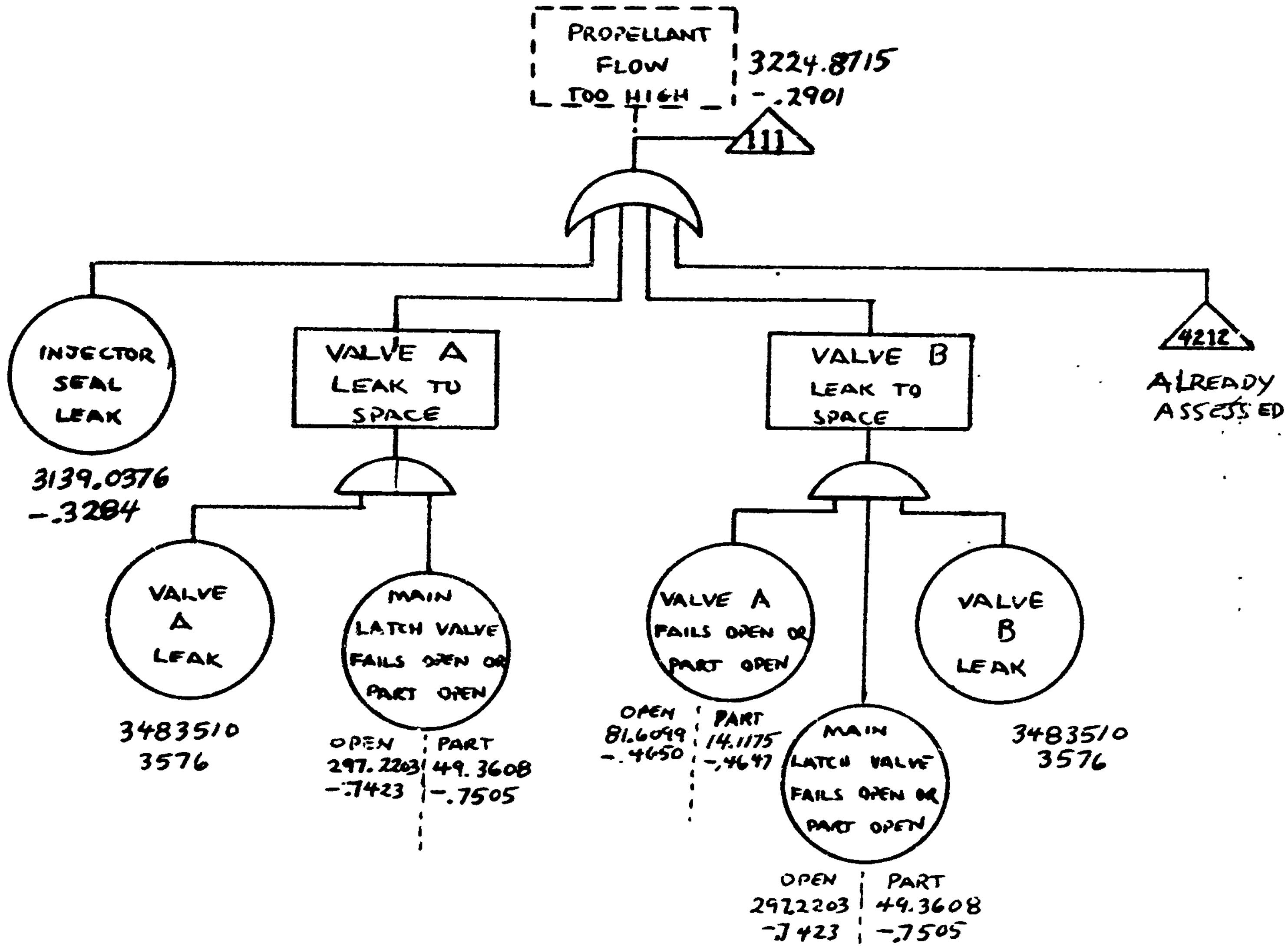
```
COMPONENT CODE?(ZZ=END)
? CBS
DESIGN CYCLE LIFE,COLD START LIFE,OP. LIFE?
? 11,1E-6,14.55
CYCLES,COLD STARTS,OP. TIME, (T=0=END)
? 11 ,1E-6,14.55
  .986334      .997729      162.3395      -.3392
CYCLES,COLD STARTS,OP. TIME, (T=0=END)
? 0,0,0

PROGRAM   BETFTA

90000 DATA 159499.4352,3.0381
90002 DATA 408.0112,-.4321
90004 DATA 162.3395,-.3392
90006 DATA 3139.0376,-.3284
90008 DATA 111.2439,-.1255
99999 END
READY.
RUN

 76/12/14. 21.33.44.
PROGRAM   BETFTA

FOR EXPLANATION LIST 80000
HOW MANY LEVELS?
? 2
EVENTS? (LOWEST FIRST) (SINGLE ASSUMED AT TOP)
? 5
DESTINATION?
 1   1 ? 1
 1   2 ? 1
 1   3 ? 1
 1   4 ? 1
 1   5 ? 1
CONDITIONALS?(0,0=SKIP)
? 0,0
GATE TYPES
 2   1 ? 1

 2   1   136.572   .859358


SYSTEM (ITERATION  1)
ALPHA    BETA    E(P)      E(P*P)     V(P)

 136.5725    .8594 .986665   .973601   .00009369

RUN COMPLETE.
```

NOTE: FOR ΔV THRUSTERS ONLY



```
PROGRAM   COMP1

OUTPUT FORMAT IS
R.05      R.5       ALPHA       BETA

COMPONENT CODE?(ZZ=END)
? IMP
DESIGN OP. LIFE=?
? .5
OPTIME=? (O=END)
? .5
  .999999     .999999    *5:99715.3910     3.0381
OPTIME=?
? 0
COMPONENT CODE?(ZZ=END)
? CBP
DESIGN CYCLE LIFE,COLD START LIFE,OP.LIFE?
? 3100,1E-6,.1
CYCLES,COLD STARTS,OP. TIME, (T=O=END)
? 3100,1E-6,.1
  .997575     .999660     841.1969      -.4327
CYCLES,COLD STARTS,OP. TIME, (T=O=END)
? 0,0,0

COMPONENT CODE?(ZZ=END)
? CBS
DESIGN CYCLE LIFE,COLD START LIFE,OP. LIFE?
? 2,1E-6,.4
CYCLES,COLD STARTS,OP. TIME, (T=O=END)
? 2,1E-6,.4
  .999564     .999928    5148.3378      -.3394
CYCLES,COLD STARTS,OP. TIME, (T=O=END)
? 0,0,0

COMPONENT CODE?(ZZ=END)
? IBF
SAME AS ISL
MISSION TIME=? (O=END)
? 43800
  .999278     .999879    3139.0376      -.3284
OPTIME=?
? 0
```

```
COMPONENT CODE?(ZZ=END)
? HET
THRUSTER CYCLES & OP.TIME
 INPUT OPTION
1=FIXED CYCLES/OP.HR., 2=SEPARATE
? 2
CYCLES=? (0=END)
? 3102
OPTIME=? (0=END)
? .5
  .976573     .994965     114.7671     -.1112
CYCLES=? (0=END)
? 0
90000 DATA  5199715.39,3.0381
90002 DATA 841.1969,-.4327,5148.0376,.3394
90004 DATA 3139.0376,-.3284,114.7671,-.1112
99999 END
READY.
RN
ILLEGAL COMMAND.
RUN

 76/12/15. 11.34.25.
PROGRAM   BETFTA

FOR EXPLANATION LIST 80000
HOW MANY LEVELS?
? 2
EVENTS? (LOWEST FIRST) (SINGLE ASSUMED AT TOP)
? 5
DESTINATION?
 1   1 ? 1
 1   2 ? 1
 1   3 ? 1
 1   4 ? 1
 1   5 ? 1
CONDITIONALS?(0,0=SKIP)
? 0,0
GATE TYPES
 2   1 ? 1

 2   1   130.359   .160562


SYSTEM (ITERATION  1)
ALPHA    BETA    E(P)      E(P*P)     V(P)

 130.3587    .1606 .991242  .982626  .00006502
```

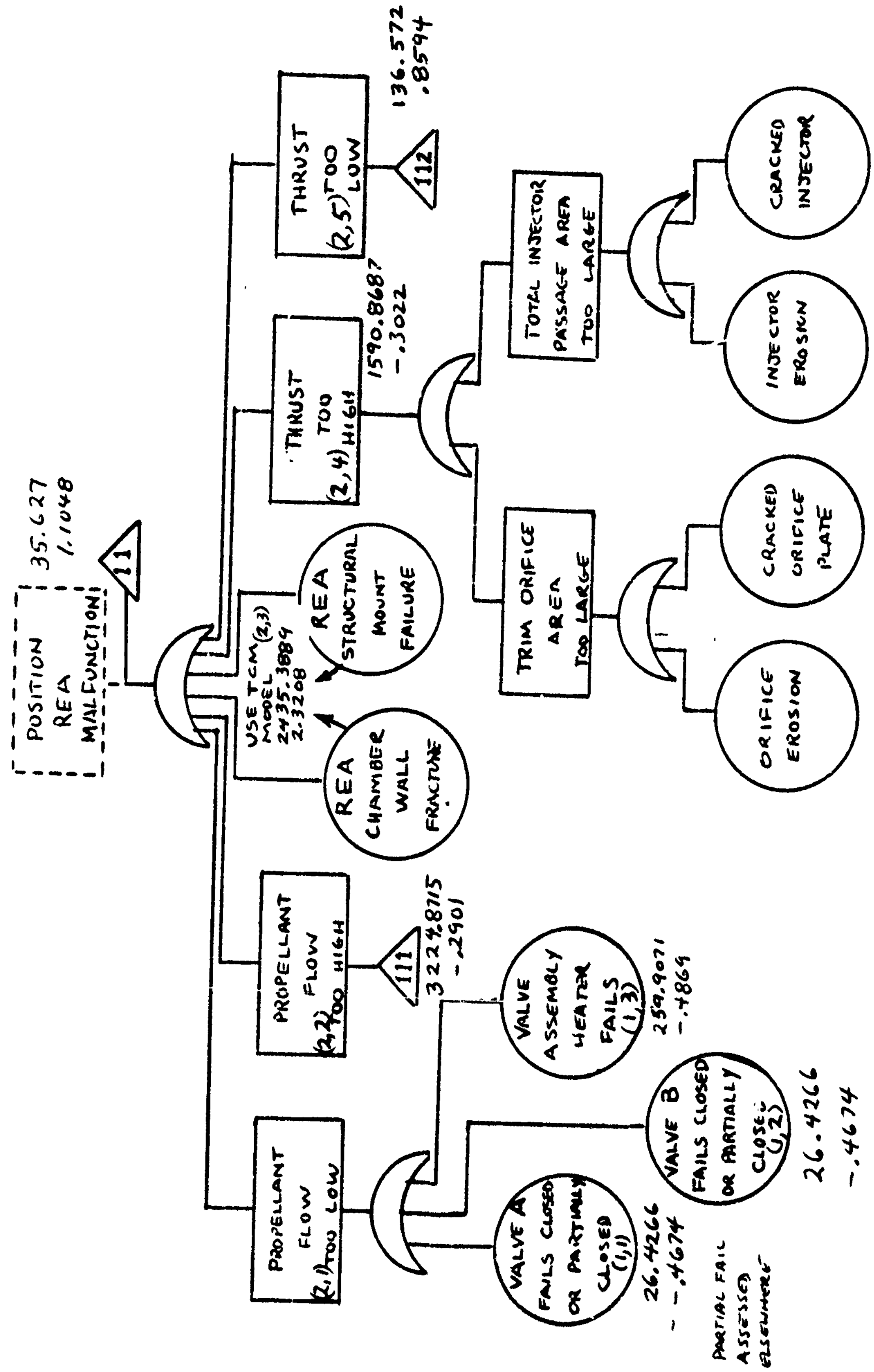

PROPELLANT FLOW TOO HIGH
3224.8715
-.2901
111
INJECTOR SEAL LEAK
3139.0376
-.3284
VALVE A LEAK TO SPACE
VALVE B LEAK TO SPACE
4212
ALREADY ASSESSED
VALVE A LEAK
3483510
3576
MAIN LATCH VALVE FAILS OPEN OR PART OPEN
OPEN
297.2203
-.7423
PART
49.3608
-.7505
VALVE A FAILS OPEN OR PART OPEN
OPEN
81.6099
-.4650
PART
14.1175
-.4647
VALVE B LEAK
3483510
3576
MAIN LATCH VALVE FAILS OPEN OR PART OPEN
OPEN
2972203
-.7423
PART
49.3608
-.7505

```
PROGRAM   COMP1

OUTPUT FORMAT IS
R.OS      R.S       ALPHA       BETA

COMPONENT CODE?(ZZ=END)
? ISL
MISSION TIME=? (0=END)
? 43800
  .999278     .999879    3139.0376     -.3284
OPTIME=?
? 0

COMPONENT CODE?(ZZ=END)
? EVLS
MISSION TIME, OPTIME=? (0,0=END)
? 43800,16.3
  .998942         .998975          3.48351E+6     3576.03
MISSION TIME. OPTIME=? (0,0=END)
? 0,0

COMPONENT CODE?(ZZ=END)
? ILVO
INPUT OPTION
1=FIXED CYCLES/MISSION HR., 2=SEPARATE
? 2
CYCLES=? (0=END)
? 1000
MISSION TIME =? (0=END)
? 43800
  .995348     .999839     297.2203      -.7423
CYCLES=? (0=END)
? 0
COMPONENT CODE?(ZZ=END)
? EVO
DESIGN CYCLE LIFE,OP. LIFE,MISSION DURATION
? 6359,16.3,43800
INPUT OPTION
1=FIXED CYCLES/OP.HR.,2=SEPARATE
? 2
CYCLES=? (0=END)
? 6359
MISSION TIME,OP. TIME (0,0=END9
? 43800,16.3
  .976315     .996878      81.6099     -.4650
CYCLES=? (0=END)
? 0
```

```
CØMPØNENT CØDE?(ZZ=END)
? EVP
DESIGN CYCLE LIFE, ØP. LIFE, MISSIØN DURATIØN
? 6359
 NØT ENØUGH DATA, TYPE IN MØRE  AT  961
? 16.3,43800
INPUT ØPTIØN
1=FIXED CYCLES/ØP.HR.,2=SEPARATE
? 2
CYCLES=? (0=END)
? 6359
MISSIØN TIME,ØP. TIME (0,0=END9
? 43800
 NØT ENØUGH DATA, TYPE IN MØRE  AT  2344
? 16.3
  .875973      .982863       14.1175      -.4647
CYCLES=? (0=END)
? 0

CØMPØNENT CØDE?(ZZ=END)
? ILVP
MISSIØN TIME=? (0=END)
? 43800
  .973039      .999133       49.3608      -.7505
ØPTIME=?
? 0

CØMPØNENT CØDE?(ZZ=END)
? ZZ
NØ SUCH CØMPØNENT

SØU       5.594 UNTS.

RUN CØMPLETE.
```

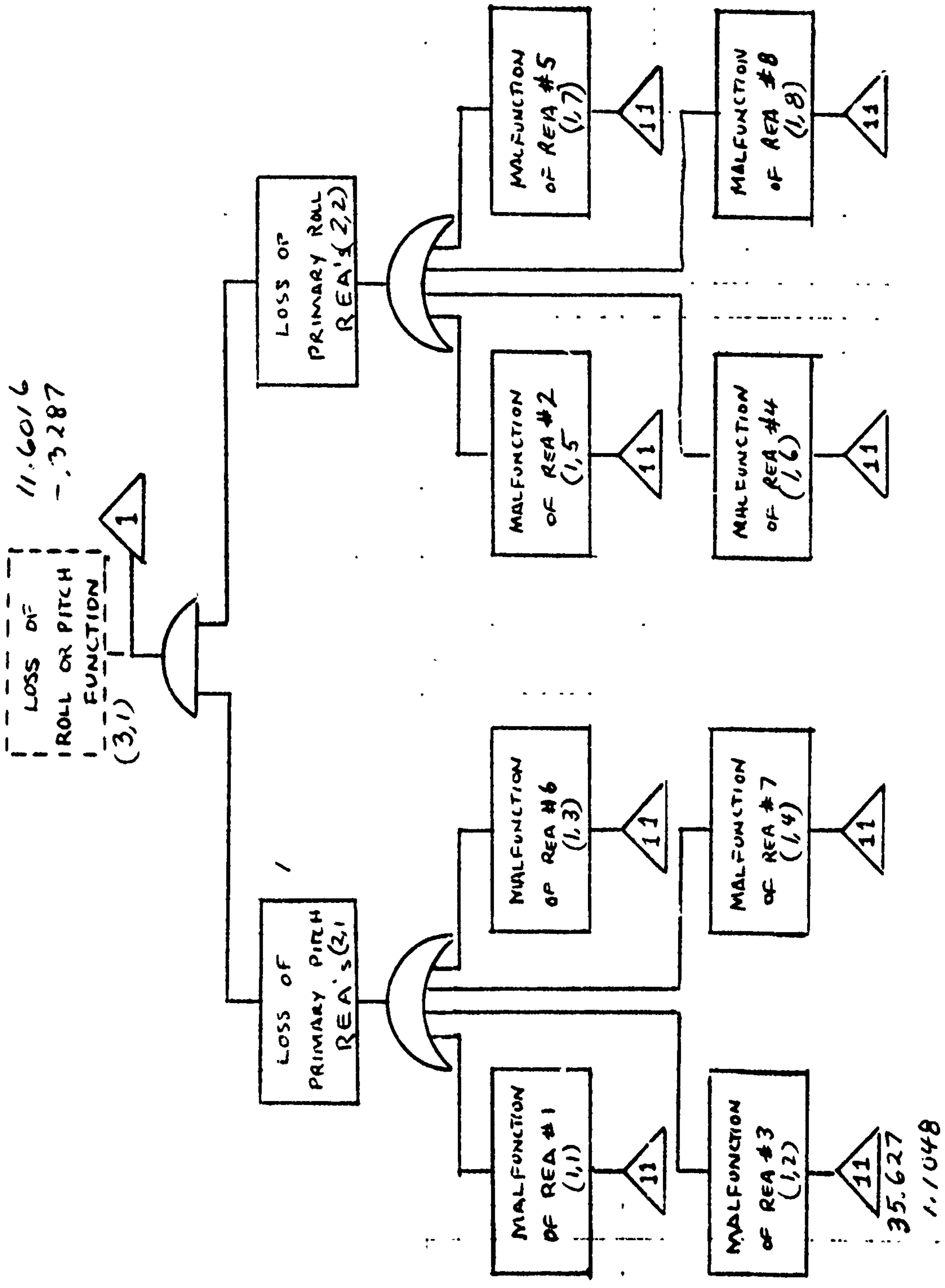
```
PROGRAM   BETFTA

90000 DATA 297.2203,-.7423,49.3608,-.7505
90002 DATA 81.6099,-.465,14.1175,-.4647
90004 DATA 297.2203,-.7423,49.3608,-.7505
90006 DATA 3483510,3576,3483510,3576
99999 END
READY.
RUN

 76/12/14. 21.12.42.
PROGRAM   BETFTA

FOR EXPLANATION LIST 80000
HOW MANY LEVELS?
? 4
EVENTS? (LOWEST FIRST) (SINGLE ASSUMED AT TOP)
? 6
? 5
? 3
DESTINATION?
 1   1 ? 2
 1   2 ? 2
 1   3 ? 3
 1   4 ? 3
 1   5 ? 4
 1   6 ? 4
 2   1 ? 2
 2   2 ? 2
 2   3 ? 3
 2   4 ? 3
 2   5 ? 3
 3   1 ? 1
 3   2 ? 1
 3   3 ? 1
CONDITIONALS?(0,0=SKIP)
? 0,0
GATE TYPES
 2   2 ? 1
 2   3 ? 1
 2   4 ? 1
 3   2 ? 2
 3   3 ? 2
 4   1 ? 1
 END OF DATA  AT  58
BASIC EXECUTION ERROR

SBU      0.729 UNTS.

RUN COMPLETE.
```

```
90000 DATA 297.2203,-.7423,49.3608,-.7505
90002 DATA 81.6099,-.465,14.1175,-.4647
90004 DATA 297.2203,-.7423,49.3608,-.7505
90006 DATA 3483510,3576,3483510,3576
99999 END
READY.
90008 DATA 3139.0376,-.3284
RUN

 76/12/14. 21.17.00.
PROGRAM   BETFTA

FOR EXPLANATION LIST 80000
HOW MANY LEVELS?
? 4
EVENTS? (LOWEST FIRST) (SINGLE ASSUMED AT TOP)
? 6
? 5
? 3
DESTINATION?
 1   1 ? 2
 1   2 ? 2
 1   3 ? 3
 1   4 ? 3
 1   5 ? 4
 1   6 ? 4
 2   1 ? 2
 2   2 ? 2
 2   3 ? 3
 2   4 ? 3
 2   5 ? 3
 3   1 ? 1
 3   2 ? 1
 3   3 ? 1
CONDITIONALS?(0,0=SKIP)
? 0,0
GATE TYPES
 2   2 ? 1
 2   3 ? 1
 2   4 ? 1
 3   2 ? 2
 3   3 ? 2
 4   1 ? 1

 2   2   56.5515 -.664897
 2   3   16.3811 -.267999
 2   4   56.5515 -.664897
 3   2   57713.8 -.657275
 3   3   540385. -.870318
 4   1   3224.87 -.290107


 SYSTEM (ITERATION  1)
 ALPHA    BETA    E(P)      E(P*P)     V(P)

 3224.8715   -.2901  .999780   .999560   .00000007
```


POSITION REA MALFUNCTION
11
35.627
1.1048
PROPELLANT FLOW (2,1) TOO LOW
PROPELLANT FLOW (2,2) TOO HIGH
111
3224.8715
-.2901
USE TCM (2,3) MODEL
2435.3889
2.3208
REA CHAMBER WALL FRACTURE
REA STRUCTURAL MOUNT FAILURE
THRUST TOO (2,4) HIGH
1590.8687
-.3022
THRUST (2,5) TOO LOW
112
136.572
.8594
TRIM ORIFICE AREA TOO LARGE
TOTAL INJECTOR PASSAGE AREA TOO LARGE
ORIFICE EROSION
CRACKED ORIFICE PLATE
INJECTOR EROSION
CRACKED INJECTOR
VALVE A FAILS CLOSED OR PARTIALLY CLOSED (1,1)
26.4266
-.4674
PARTIAL FAIL ASSESSED ELSEWHERE
VALVE B FAILS CLOSED OR PARTIALLY CLOSED (1,2)
26.4266
-.4674
VALVE ASSEMBLY HEATER FAILS (1,3)
259.9071
-.4869

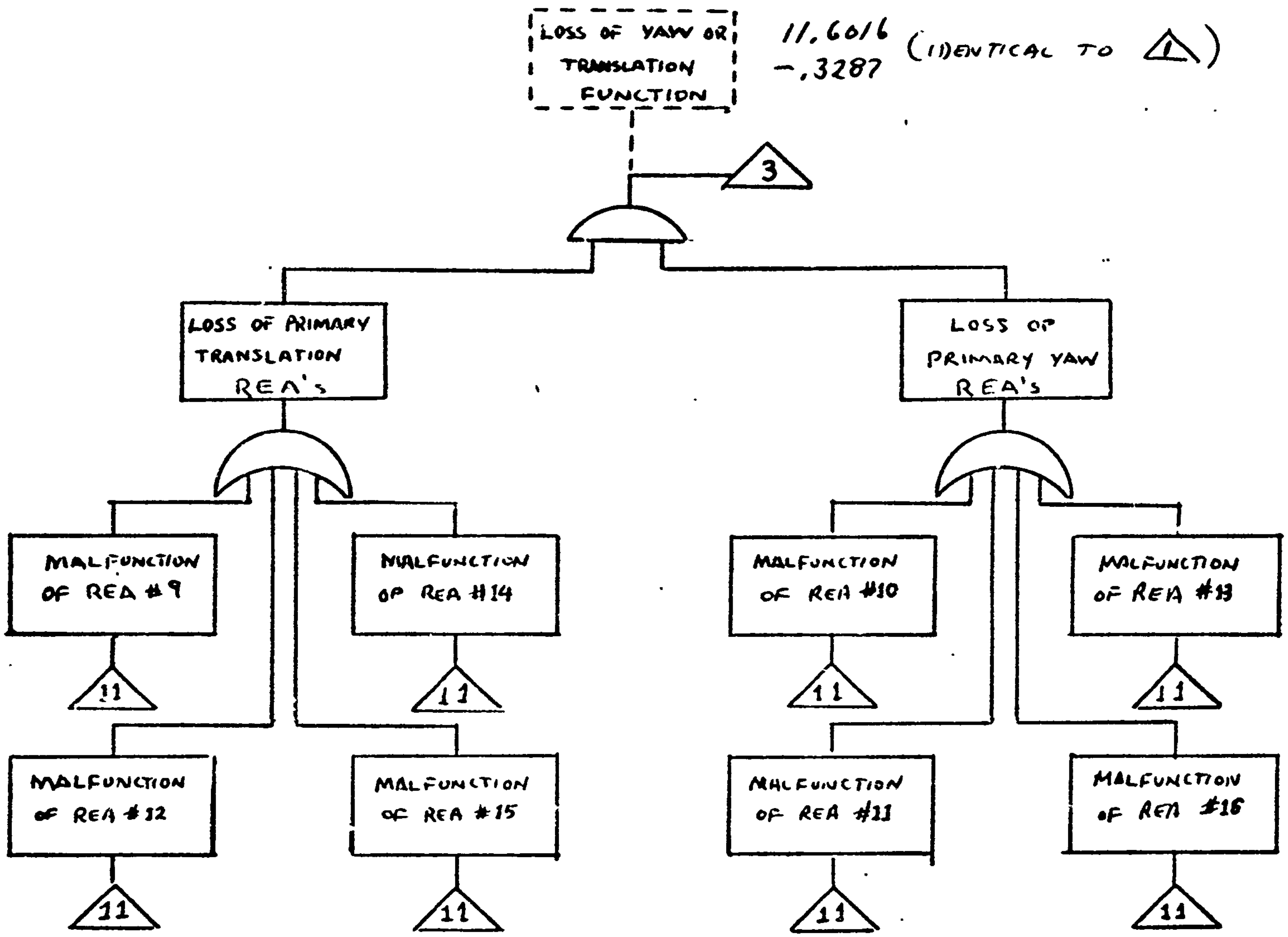
```
PROGRAM    COMP1

OUTPUT FORMAT IS
R.05       R.5        ALPHA       BETA
COMPONENT CODE?(ZZ=END)
? HLTV
MISSION TIME=? (0=END)
? 43800
 .992625     .999085     259.9071      -.4869
OPTIME=?
? 0



COMPONENT CODE?(ZZ=END)
? TCM
DESIGN CYCLE LIFE,OP.LIFE?
? 6359,16,KL
 TOO MUCH DATA, RETYPE INPUT  AT  1141
? 6359,16.3
INPUT OPTION
1=FIXED CYCLES/OP.HR., 2=SEPARATE
? 2
CYCLES =? (0=END)
? 6359
MISSION TIME,OP. TIME (0,0=END)
? 43800,16.3
 .997826     .999171    2435.3889     2.3208
CYCLES =? (0=END)
? 0

COMPONENT CODE?(ZZ=END)
? IMF
DESIGN CYCLE LIFE, OP.LIFE?
? 6359,16.3
INPUT OPTION
1=FIXED CYCLES/OP.HR., 2=SEPARATE
? 2
CYCLES=? (0=END)
? 6359
OPTIME=? (0=END)
? 16.3
 .998539     .999745    1590.3687     -.3022
CYCLES=? (0=END)
? 0
```

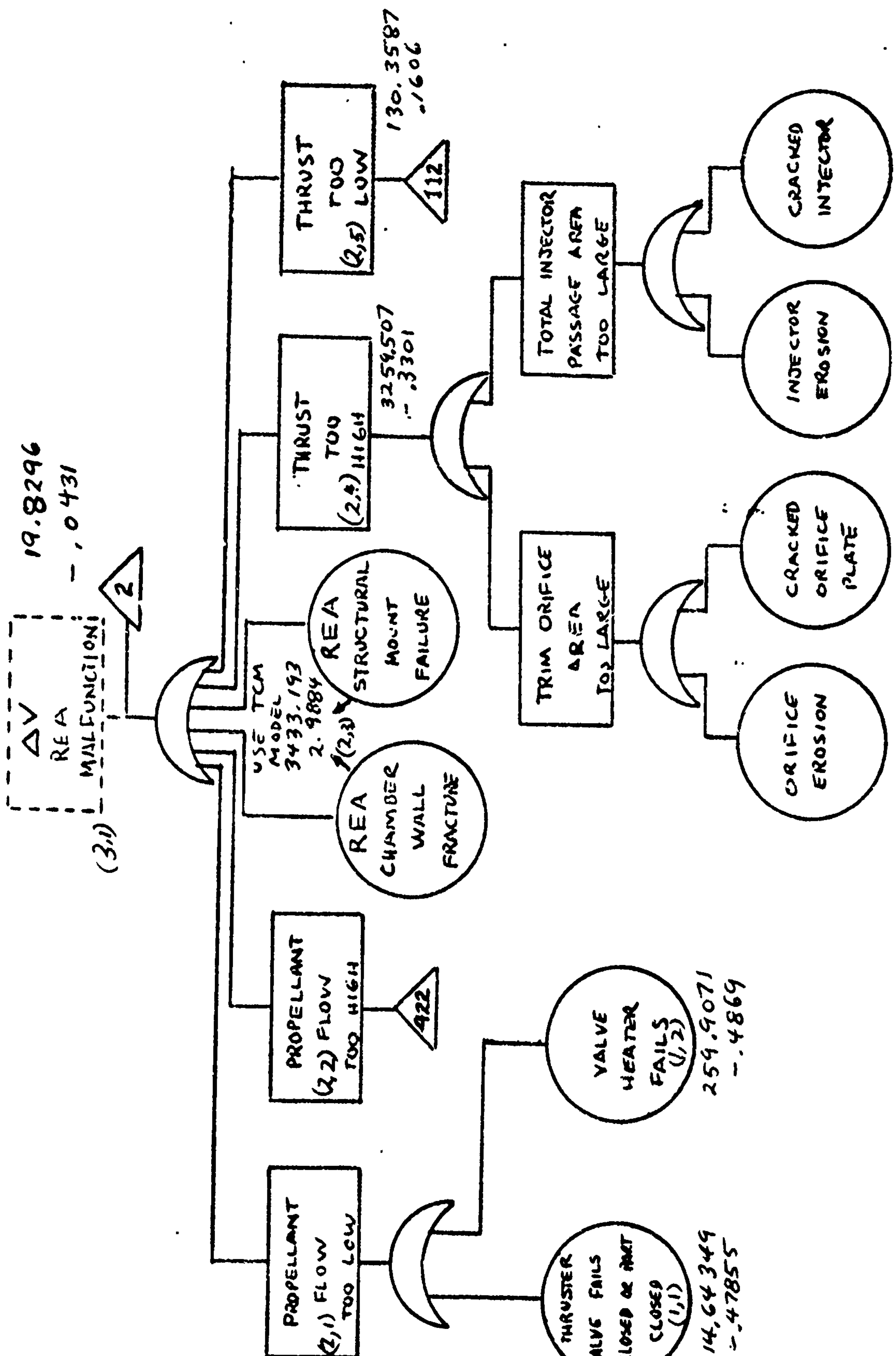
```
90000 DATA 26.4266,-.4674,26.4266,-.4674,259.9071,-.4865
90002 DATA 3224.8715,-.2901,2435.3889,2.3208
90004 DATA 1590.8687,-.3022,136.572,.8594
99999 END
READY.
RUN

 76/12/15. 11.01.14.
PRØGRAM   BETFTA

FØR EXPLANATIØN LIST 80000
HØW MANY LEVELS?
? 3
EVENTS? (LØWEST FIRST) (SINGLE ASSUMED AT TØP)
? 3
? 5
DESTINATIØN?
 1  1 ? 1
 1  2 ? 1
 1  3 ? 1
 2  1 ? 1
 2  2 ? 1
 2  3 ? 1
 2  4 ? 1
 2  5 ? 1
CØNDITIØNALS?(0,0=SKIP)
? 0,0
GATE TYPES
 2  1 ? 1
 3  1 ? 1

 2  1  27.4107   .172197
 3  1  35.627    1.10484


SYSTEM (ITERATIØN  1)
ALPHA   BETA   E(P)     E(P*P)    V(P)

  35.6270  1.1048 .945656  .895559  .00129344


 END ØF DATA  AT  58
BASIC EXECUTIØN ERRØR

SBU      0.752 UNTS.

RUN CØMPLETE.
```



LOSS OF ROLL OR PITCH FUNCTION (3,1)
11.6016
-.3287
1
LOSS OF PRIMARY PITCH REA's (2,1
LOSS OF PRIMARY ROLL REA's (2,2)
MALFUNCTION OF REA #1 (1,1)
MALFUNCTION OF REA #3 (1,2)
MALFUNCTION OF REA #6 (1,3)
MALFUNCTION OF REA #7 (1,4)
MALFUNCTION OF REA #2 (1,5
MALFUNCTION OF REA #4 (1,6)
MALFUNCTION OF REA #5 (1,7)
MALFUNCTION OF REA #8 (1,8)
11
35.627
1.1048

```
90000 DATA 3F.627,1.1048,35.6270,1.1048
90002 DATA 35.6270,1.1048,35.6270,1.1048
90004 DATA 35.6270,1.1048,35.6270,1.1048
90006 DATA 35.6270,1.1048,35.6270,1.1048
99999 END
READY.
RUN

 76/12/15. 11.07.19.
PRØGRAM   BETFTA

FØR EXPLANATIØN LIST 80000
HØW MANY LEVELS?
? 3
EVENTS? (LØWEST FIRST) (SINGLE ASSUMED AT TØP)
? 8
? 2
DESTINATIØN?
 1  1 ? 1
 1  2 ? 1
 1  3 ? 1
 1  4 ? 1
 1  5 ? 2
 1  6 ? 2
 1  7 ? 2
 1  8 ? 2
 2  1 ? 1
 2  2 ? 1
CØNDITIØNALS?(0,0=SKIP)
? 0,0
GATE TYPES
 2  1 ? 3
 2  2 ? 3
 3  1 ? 4

 2  1  7.79209  1.11015
 2  2  7.79209  1.11015
 3  1  11.6016 -.3287


SYSTEM (ITERATIØN  1)
ALPHA    BETA    E(P)      E(P*P)     V(P)

  11.6016  -.3287 .949423  .904769  .00336431
```

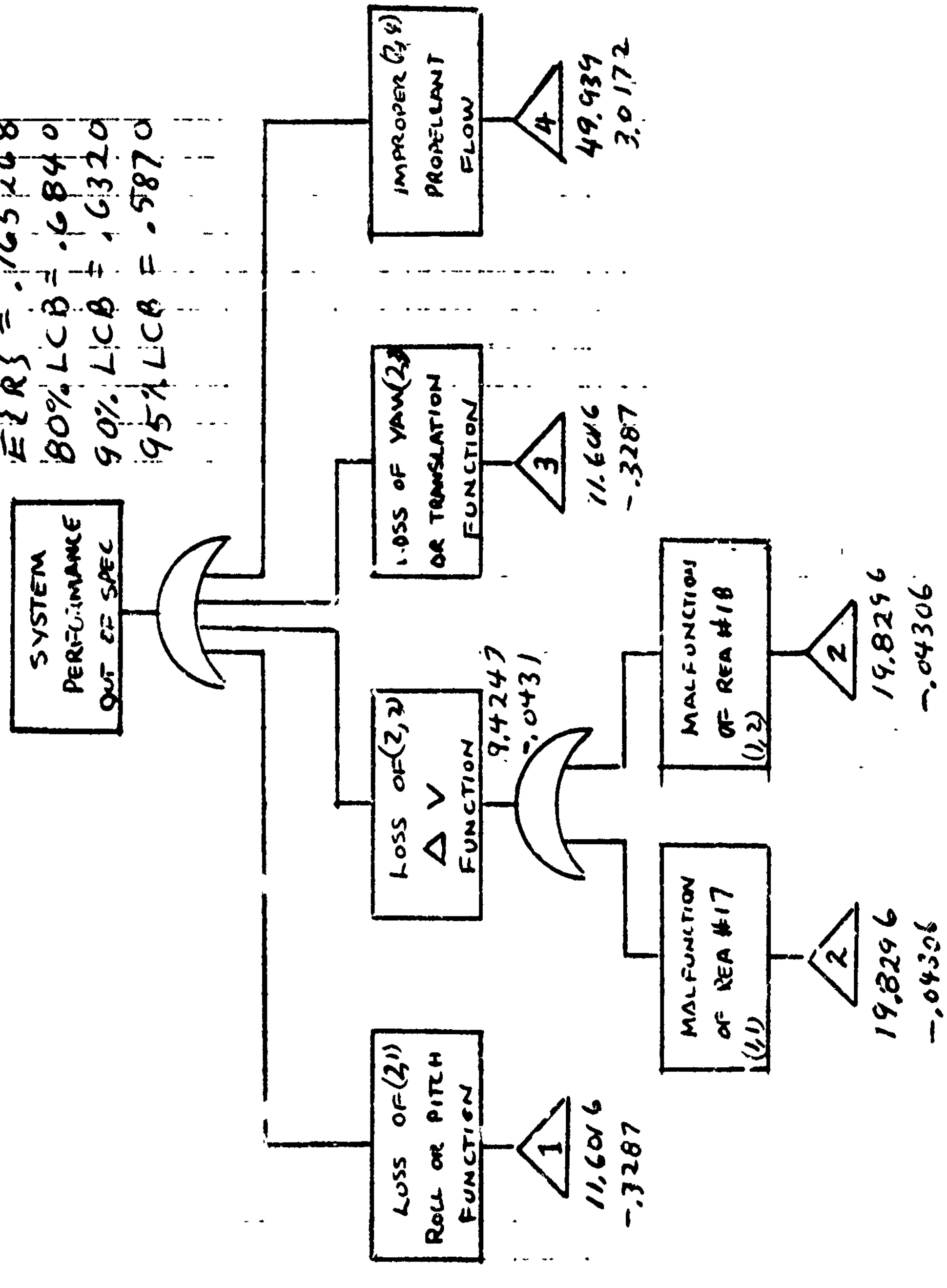

LOSS OF YAW OR TRANSLATION FUNCTION
11,6016
-,3287
(IDENTICAL TO 1)
3
LOSS OF PRIMARY TRANSLATION REA's
LOSS OF PRIMARY YAW REA's
MALFUNCTION OF REA #9
MALFUNCTION OF REA #14
MALFUNCTION OF REA #10
MALFUNCTION OF REA #13
MALFUNCTION OF REA #12
MALFUNCTION OF REA #15
MALFUNCTION OF REA #11
MALFUNCTION OF REA #16
11



ΔV
REA
MALFUNCTION
(3,1)
19.8296
-.0431
2
PROPELLANT
(2,1) FLOW
TOO LOW
PROPELLANT
(2,2) FLOW
TOO HIGH
422
REA
CHAMBER
WALL
FRACTURE
USE TCM
MODEL
3433.193
2.9884
(2,3)
REA
STRUCTURAL
MOUNT
FAILURE
THRUST
TOO
(2,4) HIGH
3254.507
-.3301
THRUST
TOO
(2,5) LOW
130.3587
.1606
112
THRUSTER
VALVE FAILS
CLOSED OR PART
CLOSED
(1,1)
14.64349
-.47855
VALVE
HEATER
FAILS
(1,2)
259.9071
-.4869
TRIM ORIFICE
AREA
TOO LARGE
TOTAL INJECTOR
PASSAGE AREA
TOO LARGE
ORIFICE
EROSION
CRACKED
ORIFICE
PLATE
INJECTOR
EROSION
CRACKED
INJECTOR

```
PRØGRAM   CØMP1

ØUTPUT FØRMAT IS
R.05      R.5        ALPHA       BETA

CØMPØNENT CØDE?(ZZ=END)
? HLTV
MISSIØN TIME=? (0=END)
? 43800
  .992625      .999085     259.9071      -.4869
ØPTIME=?
? 0

CØMPØNENT CØDE?(ZZ=END)
? TCM
DESIGN CYCLE LIFE,ØP.LIFE?
? 3102,.5
INPUT ØPTIØN
1=FIXED CYCLES/ØP.HR., 2=SEPARATE
? 2
CYCLES =? (0=END)
? 3102
MISSIØN TIME,ØP. TIME (0,0=END)
? 43800..5
  .998161      .999217    3433.1930      2.9884
CYCLES =? (0=END)
? 0

CØMPØNENT CØDE?(ZZ=END)
? IMF
DESIGN CYCLE LIFE, ØP.LIFE?
? 3102,.5
INPUT ØPTIØN
1=FIXED CYCLES/ØP.HR., 2=SEPARATE
? 2
CYCLES=? (0=END)
? 3102
ØPTIME=? (0=END)
? .5
  .999305      .999884    3259.5070      -.3301
CYCLES=? (0=END)
? 0
```

```
90000 DATA 14.64349,-.47855,259.9071,-.4869
90002 DATA 3433.193,2.9884,3259.507,-.3301,130.3587,.1606
99999 END
READY.
RUN

76/12/15. 12.37.25.
PROGRAM   BETFTA

FOR EXPLANATION LIST 80000
HOW MANY LEVELS?
? 3
EVENTS? (LOWEST FIRST) (SINGLE ASSUMED AT TOP)
? 2
? 4
DESTINATION?
 1  1 ? 1
 1  2 ? 1
 2  1 ? 1
 2  2 ? 1
 2  3 ? 1
 2  4 ? 1
CONDITIONALS?(0,0=SKIP)
? 0,0
GATE TYPES
 2  1 ? 1
 3  1 ? 1

 2  1  15.5557 -.414498
 3  1  19.8296 -4.30613E-2


SYSTEM (ITERATION  1)
ALPHA    BETA    E(P)      E(P*P)     V(P)

  19.8296  -.0431 .956077  .915925  .00184293


 END OF DATA  AT  58
BASIC EXECUTION ERROR

SBU      0.701 UNTS.

RUN COMPLETE.
```


SYSTEM PERFORMANCE OUT OF SPEC
E{R} = .765248
80% LCB = .6840
90% LCB = .6320
95% LCB = .5870
IMPROPER (2,4) PROPELLANT FLOW
4
49.939
3.0172
LOSS OF YAW (2,3) OR TRANSLATION FUNCTION
3
11.6016
-.3287
LOSS OF (2,2) ΔV FUNCTION
9.4247
-.0431
MALFUNCTION OF REA #18 (1,2)
2
19.8296
-.04306
MALFUNCTION OF REA #17 (1,1)
2
19.8296
-.04306
LOSS OF (2,1) ROLL OR PITCH FUNCTION
1
11.6016
-.3287

```
90000 DATA 19.8296,-.04306,19.8296,-.04306
RUN

 76/12/15.  14.30.49.
PRØGRAM   BETFTA

FØR EXPLANATIØN LIST 80000
HØW MANY LEVELS?
? 2
EVENTS? (LØWEST FIRST) (SINGLE ASSUMED AT TØP)
? 2
DESTINATIØN?
 1   1 ? 1
 1   2 ? 1
CØNDITIØNALS?(0,0=SKIP)
? 0,0
GATE TYPES
 2   1 ? 3

 2   1   9.42466 -4.30988E-2


SYSTEM (ITERATIØN  1)
ALPHA   BETA   E(P)     E(P*P)    V(P)

   9.4247   -.0431 .915925  .845139  .00621942
```

```
PROGRAM   BETAL1

RUN IN DOUBLE PRECISION
PERMIT NEGATIVE BETA?
? 1
TYPE OF INPUT?
1=PARAMETERS,2=MOMENTS (MEAN & VAR)
? 1
HOW MANY COMPONENTS?
? 4
VALUES? (THIRD VALUE IS COST OF FIRST TEST)
? 11.6016,-.3287,10
? 9.4247,-.0431,10
? 11.6016,-.3287,10
? 49.939,3.0172,10
DISPLAY COMPONENT VALUES?
? 1

NO. ALPHA   BETA  E(P)     E(P*P)    V(P)       COST

 1   11.60  -.33  .949423  .904769  .00336433    10.00
 2    9.42  -.04  .915926  .845139  .00621937    10.00
 3   11.60  -.33  .949423  .904769  .00336433    10.00
 4   49.94  3.02  .926902  .860358  .00121086    10.00


FOR SYSTEM


E(R)      E(R*R)     V(R)

.765268   .595227   .00959154


CLOSURE
 .999564
LOWER CONF. BOUNDS
80  .6840  90  .6320  95  .5870
```

EXAMPLE III M-out-of-N Redundance

In addition to standby redundancy (exemplified by the dual PCC's and Thrusters of the Mercury ion system of Example I) a system can employ m-out-of-n redundancy where n units are all in operation but only m are required for successful mission completion. There are two types of m-out-of-n dedundancy, identical and independent. The identical case is that in which all (n) components not only have identical failure rate expectations and variances, but are of the same type (e.g. compositor resistor of the same rating and resistance value and hence likely to come from the same manufacturing lot). The independent case includes (1) similar components with identical failure rate expectation and variances, coming from different manufacturing lots and (2) dissimilar components, regardless of their failure rate and variance values, meeting the m-out-of-n criterion.

A. Identical M-out-of-N Redundancy

The colloid thruster system presents a good example of identical m-out-of-n redundancy. Twelve identical thrust modules make up the thrust unit of the system. However the system can successfully complete a mission with less than all twelve modules operating. First the lower bound and median reliability, and α and β values for the Colloid Thruster Module (CTM) component are determined using COMP1. The reliability at the 8000 operating hour will be computed.

```
PRØGRAM   CØMP1

ØUTPUT FØRMAT IS
R.05      R.5       ALPHA        BETA

CØMPØNENT CØDE?(ZZ=END)
? CTM
ØPTIME=? (O=END)
? 8000
  .952067     .998162      28.0522      -.7334
ØPTIME=?
? 0
```

Program BETSB3 has been developed for the Identical M-out-of-N case and is next used. For the purpose of this example ten modules of the total twelve will be assumed to be required. Further the component input data will use the parameter option, that is, the α and β output of COMP1 will be used. (BETSB3 can also accept input information in the form of the mean value of reliability and the variance). BETSB3 output provides α, β, $E\{R\}$, $E\{R^2\}$ and $V\{R\}$ for the subsystem of the twelve modules.

```
PRØGRAM   BETSB3

M-ØF-N IDENTICAL
RUN IN DØUBLE PRECISIØN
TYPE ØF INPUT(1=PARAM,2=MEAN&VAR)
? 1
HØW MANY CØMPØNENTS?
? 12
HØW MANY REQ'D?
? 10
VALUES
? 28.0522,-.7334

SUBSYSTEM
ALPHA    BETA       E(R)        E(R*R)      V(R)

  8.3306  -.9700  .99679445   .99390757   .00030841


IF NEGATIVE SUBSYSTEM BETA NØT ALLØWED
SUBSYSTEM
ALPHA    BETA       E(R)        E(R*R)      V(R)

309.9585   .0000  .99679445   .99360938   .00001021
```

Note the first value of BETA in the output is negative. This implies a lognormal uncertainty distribution that has degenerated to a J shape. If for some application the degenerated lognormal is not permissable, the program in this situation sets β equal to zero (the lowest possible value for β without curve shape degeneration) and recomputes the other parameters. The principal differences are in the value of α and the variance $V\{R\}$. The latter parameter will always be understated if the constraint of $\beta \geq 0$ (non degenerate log normal uncertainty distribution) is applied. The degree of understatement will vary from case to case.

B. Independent M-out-of-N Redundancy

Program BETSB2 was developed to address the independent M-out-of-N case. It was developed to present the complete M-out-of-N situation, even though the systems included in this study do not employ such a configuration. For the purpose of presenting a comparative example the colloid thruster module (CTM) used in example IIIA will be used here AS IF the independ. m-out-of-n criteria had been met.

```
PRØGRAM   BETSB2

M-ØF-N,INDEPENDENT
RUN IN DØUBLE PRECISIØN
TYPE ØF INPUT(1=PARAM,2=MEAN&VAR)
? 1
HØW MANY CØMPØNENTS?
? 12
HØW MANY REQ'D?
? 10
SAME PARAMS?(1=YES,0=NØ)
? 1
VALUES?
? 28.0522,-.7334
SUBSYSTEM
ALPHA    BETA       E(R)        E(R*R)      V(R)

*1498.6459   -.7667   .99984445   .999689031   .00000010
 1498.65


IF NEGATIVE SUBSYSTEM BETA NØT ALLØWED
SUBSYSTEM
ALPHA    BETA       E(R)        E(R*R)      V(R)

*6426.8587    .0000   .99984445   .999688951   .00000002
 6426.86
```

Again a negative value for BETA resulted, and as in BETSB3, the $\beta \geq 0$ alternative was computed and presented.

APPENDIX B

AGGREGATES OF BETA - DISTRIBUTED VARIATES

APPENDIX B

AGGREGATES OF BETA - DISTRIBUTED VARIATES

Consider a set of N stochastically independent events whose probabilities of occurrence (nonoccurrence) are represented by P_i $(1-P_i = q_i)$, i = 1, 2, ...N. Suppose that the P_i (q_i) are themselves Beta - distributed random variables, so that the probability density function for P_i may be written

$$f(P_i) = \frac{\Gamma(\alpha_i + \beta_i + 2)}{\Gamma(\alpha_i + 1)\,\Gamma(\beta_i + 1)} P_i^{\alpha_i} \left(1 - P_i\right)^{\beta_i}, \quad \begin{cases} \alpha_i > -1 \\ \beta_i > -1 \end{cases} \tag{1}$$

where the α_i, B_i may, but need not, be alike for some or all i. It is well known that

$$E\left\{P_i\right\} = \frac{\alpha_i + 1}{\alpha_i + \beta_i + 2} \tag{2}$$

$$E\left\{P_i^2\right\} = \frac{(\alpha_i + 1)\ (\alpha_i + 2)}{(\alpha_i + \beta_i + 2)\ (\alpha_i + \beta_i + 3)} \tag{3}$$

where $E\left\{\ \right\}$ denotes the expected value of the variable in braces.

We shall be interested in the probabilities of occurrence of higher-level events bearing known relationships to the event sets under consideration. Specifically, we shall consider three relationships of special interest in reliability. Letting P_i represent the probability of occurrence of "Success" of the i th component and R the probability of occurrence of a higher-level event (the "success" of an aggregate of components corresponding to the N events), we have

$$R = \prod_{i=1}^{N} P_i \tag{4}$$

corresponding to a "series" (N - of - N) system,

$$R = 1 - \prod_{i=1}^{N} q_i \tag{5}$$

corresponding to a "redundant" (1 - of - N) system, and

$$R = \sum_{X=M}^{N} \binom{N}{X} P_i^{X} q_i^{N-X} \;, \; P_1 = P_2 = \ldots = P_i = \ldots = P_N \tag{6}$$

corresponding to an "M - of - N redundant" system (of N like components).

In each case, we shall desire a distributional description of R in addition to $E\{R\}$ and the variance $V\{R\}$

The relationship between the P_i and R involves further independence considerations. If the P_i are distributed differently <u>or</u> identically and independently (i.i.d.) the series case <u>is</u>

$$E\{R\} = \prod_{i=1}^{N} E\{P_i\} = \prod_{i=1}^{N} \frac{\alpha_i + 1}{\alpha_i + \beta_i + 2} \tag{7}$$

$$E\{R^2\} = \prod_{i=1}^{N} E\{P_i^2\} = \prod_{i=1}^{N} \frac{(\alpha_i+1)\;(\alpha_i+2)}{(\alpha_i+\beta_i+2)\;(\alpha_i+\beta_i+3)} \tag{8}$$

and, as in all cases, the variance is

$$V\{R\} = E\{R^2\} - \left[E\{R\}\right]^2 \tag{9}$$

It is known that Beta-distributed P_i do <u>not</u> lead to a Beta-distributed R, and exact description and evaluation of the distribution of R are cumbersome at best. For integer α_i and β_i, exact evaluation is possible through a Mellin integral transform described by Springer and Thompson . The results for a number of cases have been compared to those obtained by fitting a Beta-distributed to $E\{R\}$, $V\{R\}$ and performing numerical integration; the cumulants generally agree to three decimal places or better.

We regard the fitting of a Beta distribution as satisfactory and appropriate. The fitting process is straightforward; writing

$$f(R) = \frac{\Gamma(A+B+2)}{\Gamma(A+1)\Gamma(B+1)} R^{A} (1-R)^{B}$$

we have*

$$B = 1 - \frac{E\{R^2\}}{E\{R\}} \cdot \frac{E\{R\}-1}{E\{R\} - \frac{E\{R^2\}}{E\{R\}}} \tag{10}$$

$$A = [B+1] \cdot \frac{E\{R\}}{[1-E\{R\}]} - 1 \tag{11}$$

For the redundant (1 - of - N) case with the P_i independent

$$E\{R\} = 1 - \prod_{i=1}^{N} \left[1-E\{p_i\}\right] = 1 - \prod_{i=1}^{N} E\{q_i\} = \prod_{i=1}^{N} \frac{\beta_i+1}{\alpha_i+\beta_i+2} \tag{12}$$

$$E\{R^2\} = 1-2\left[1-E\{R\}\right]+E\{(1-R)^2\} = 1-2\, E\{q_i\} \prod_{i=1}^{N} E\{q_i\} + \prod_{i=1}^{N} E\{q_i^2\}$$

$$= 1-2 \prod_{i=1}^{N} \frac{\beta_i+1}{\alpha_i+\beta_i+2} + \prod_{i=1}^{N} \frac{(\beta_i+1)\quad(\beta_i+2)}{(\alpha_i+\beta_i+2)\ (\alpha_i+\beta_i+3)} \tag{13}$$

Since the distributiions of R and (1 - R) are perfectly symmetrical, with $E\{R\} = 1 - E\{1 - R\}$ and $V\{R\} = V\{1 - R\}$, the validity of the approximation for the series case is not impaired in the redundant case.

---

* Under some conditions, this procedure leads to $B<0$ (or $A<0$), implying that the behavior of f(R) near R = 1 (R = 0) is inconsistent with the component p.d.f.'s if all $B_i > 0$ (all $\alpha_i > 0$). If this is unacceptable, set B = 0 (A = 0); this also results in an arbitrary reduction in V R .

Of interest also are the relationships involving independence of occurrence, but not of prior probabilities of occurrence. By this is meant that for any two events, say the success events J and K among the N events,

$$P_K \mid J = P_K$$

but

$$P_K = P_j$$

where P_K and P_j remain Beta-distributed random variables (i.e., α_K , α_j, $B_K = B_j$). A physical example of such a situation would arise if a subsystem involved two pyrotechnic devices drawn from the same production lot, the reliability of devices from that lot being unknown but constituting a random sample from a Beta distribution describing the lot-to-lot variation in reliability. The corresponding models are not restricted to two such devices, for the series case,

$$E\left\{R\right\} = E \quad Pi^N = \prod_{i=1}^{N} \frac{\alpha + i}{\alpha + \beta + i + 1} \tag{12}$$

$$E\left\{R^2\right\} = E\left\{Pi^{2N}\right\} = \prod_{i=1}^{2N} \frac{\alpha + i}{\alpha + \beta + i + 1} \tag{13}$$

where $\alpha = \alpha_1 = \alpha_2 = \ldots. = \alpha_N \quad = \beta_1 = \beta_2 = \ldots. = \beta_N$.

Similarly, for the redundant (1-of N)case

$$E\left\{R\right\} = 1 - E\left\{9_i^N\right\} = 1 - \prod_{i=1}^{N} \frac{\beta + 1}{\alpha + \beta + i + 1} \tag{14}$$

$$E\left\{R^2\right\} = 1-2[1-E\left\{R\right\}] + E\left\{(1-R)^2\right\} = 1-2E\left\{9_i^N\right\} + E\left\{9^{2N}\right\} \tag{15}$$

$$= 1-2 \prod_{i=1}^{N} \frac{\beta + 1}{\alpha + \beta + i + 1}$$

Among the interesting consequences is that the series-case $E\{R\}$ is greater for identical than for i.i.d. components, while the converse is true in the redundant case.

It should be noted that combinations of identical with different or i.i.d. components can be handled by applying the procedure in two stages.

The M-of-N redundant case with different or i.i.d. components is more complex due to nonzero covariance terms associated with the various "success" outcomes, even though the components as such are independent. To illustrate this, consider a three-component aggregate with 2-of-3 redundancy. Let the component non-failure events be denoted by J,K,L with $P(J) = P_j$, $P(K) = P_k$, $P(L) = P_l$, and the system success event S with $P(S) = R$. Then

$$S=(J\cap K\cap L)\cup(\overline{J}\cap K\cap L)\cup(J\cap\overline{K}\cap L)\cup(J\cap K\cap\overline{L})$$

$$R=P_j\cdot P_k\cdot P_l+q_jP_kP_l+P_jq_kP_l+P_jP_kq_l$$

Since J,K and L are independent,

$$E\{R\}=E\{P_j\}\cdot E\{P_k\}\cdot E\{P_l\}+E\{q_j\}\cdot E\{P_k\}\cdot E\{P_l\}$$
$$+E\{P_j\}\cdot E\{q_k\}\cdot E\{P_l\}+E\{P_j\}\cdot E\{P_k\}\cdot E\{q_l\}$$

but

$$V\{R\} = V\{1-R\} \quad V\{P_jP_kP_l + q_jP_kP_l\}$$
$$+ V\{P_jq_kP_l\}+V\{P_jP_kq_l \;\; j\}$$

rather,

$$V\{R\}=V\{1-R\}=V\{P_jP_kP_l\}+V\{q_jP_kP_l\}$$
$$+V\{P_jq_kP_l\}+V\{P_jP_kq_l\}$$
$$+2\,\mathrm{COV}\{P_jP_kP_l,\ q_jP_kP_l\}$$

$$\begin{aligned}
&+2\ \mathrm{COV}\left\{P_j P_k P_l,\ P_j q_k P_l\right\}\\
&+2\ \mathrm{COV}\left\{P_j P_k P_l,\ P_j P_k q_l\right\}\\
&+2\ \mathrm{COV}\left\{q_j P_k P_l,\ P_j q_k P_l\right\}\\
&+2\ \mathrm{COV}\left\{q_j P_k P_l,\ P_j P_k q_l\right\}\\
&+2\ \mathrm{COV}\left\{P_j q_k P_l,\ P_j P_k q_l\right\}
\end{aligned} \tag{16}$$

Additional notation is useful in generalizing this. Denoting by Y the number of distinct success states in M-of-N reduncancy,

$$Y = \sum_{X=M}^{N} \binom{N}{X} \tag{17}$$

Let s, t be the indices of any two of the Y distinct success states, and R_s (R_t) the probability of occurrence of the s'th (t'th) such state. Then

$$V\left\{R\right\} = V\left\{\sum_{s=1}^{N} R_s\right\} = \sum_{s=1}^{Y} V\left\{R_s\right\} + 2 \sum_{s=1}^{Y} \sum_{t=s+1}^{Y} \mathrm{COV}(R_s, R_t) \tag{18}$$

where

$$\mathrm{COV}\left\{R_s R_t\right\} = E\left\{R_s R_t\right\} - E\left\{R_s\right\} E\left\{R_t\right\} \tag{19}$$

now define

$h\ (i,r) = 1$ if the r'th success state implies component success I (20a)

$h\ (i,r) = 0$ if the r'th success state implies component failure I (20b)

For example, if the r'th success state is defined by $J \cap K \cap L$,

$$h(j,r) = 1$$

$$h(k,r) = 1$$

$$h(l,r) = 0$$

then

$$E\left\{R_s R_t\right\} = \prod_{i=1}^{N} \left[\prod_{x=1}^{h(i,s)+h(i,t)} (\alpha_i + x) \cdot \prod_{x=1}^{2-h(i,s)-h(i,t)} (\beta_i + x) \right] \quad (21)$$

where

$$\prod_{x=1}^{0} (\alpha_i + x) = \prod_{x=1}^{0} (\beta_i + x) = 1$$

$$E\left\{R_r\right\} = \prod_{i=1}^{N} \frac{(\alpha_i+1)^{h(i,r)} (\beta_i+1)^{[1-h(i,r)]}}{\alpha_i = \beta_i + 2} \quad (22)$$

$$V\left\{R_r\right\} = \prod_{i=1}^{N} \frac{[(\alpha_i+1)(\alpha_i+2)]^{h(i,r)} [(\beta_i+1)(\beta_i+2)]^{[1-h(i,r)]}}{(\alpha_i+\beta_i+2)(\alpha_i+\beta_i+3)} - [E\left\{R_r\right\}]^2 \quad (23)$$

allowing evaluation of (19) and (18). Of course,

$$E\left\{R\right\} = \sum_{r=1}^{N} E\left\{R_r\right\} \quad (24)$$

Obvious computational simplifications are available when the components are i.i.d., but care must be exercised because E $R_s R_t$ depends on identity/nonidentity of the failed/unfailed components in the s'th and t'th states. For example, if the 2nd state is defined by J K L, the 5th by J K L, and the 7th by J K L, usually

$$E\left\{R_2 R_5\right\} \quad E\left\{R_2 R_7\right\}$$

(This example is chosen for simplicity; normally 1-of-3 redundancy would be evaluated as an ordinary redundant case.)

There remains the M-ofN redundant case for identical components. Expressions (18), (19), and (24) remain valid, but (21) - (23) are replaced by different (and simpler) forms.

Count the number of component successes in the s'th and t'th case and denote these by H_s and H_t, respectively; i.e.

$$H_s = \sum_{i=1}^{N} h\ (i,s)$$

$$H_t = \sum_{i=1}^{N} h\ (i,t)$$

then

$$E\left\{R_s R_t\right\} = \prod_{i=1}^{H_s+H_r} (\alpha+i) \prod_{i=1}^{2N-H_s H_t} (\beta+i) \cdot \prod_{i=1}^{2N} \frac{1}{(\alpha+\beta+i+1)} \qquad (25)$$

where again

$$E\left\{R_r\right\} = \prod_{i=1}^{H_r} (\alpha+i) \cdot \prod_{i=1}^{N-H_r} (\beta+i) \cdot \prod_{i=1}^{N} \frac{1}{(\alpha+\beta+i+1)} \qquad (26)$$

$$V\left\{R_r\right\} = \prod_{i=1}^{2H_r} (\alpha+i) \cdot \prod_{i=1}^{2(N-H_r)} (\beta+i) \prod_{i=1}^{2N} \frac{1}{(\alpha+\beta+i+1)} \qquad (27)$$

APPENDIX C

BIBLIOGRAPHY

This bibliography is designed to enlighten the reader as to documents that are available in the field of reliability estimation procedures for electric and thermochemical propulsion systems. The bibliography is divided into eight separate sections:

- Electric (Ion)
- Electric (Colloid)
- Electric (Pulsed Plasma)
- Electric (General)
- Thermo-Chemical (Electro-Thermal Monopropellant)
- Thermo-Chemical (Catalytic Monopropellant)
- Thermo-Chemical (Bipropellant)
- Thermo-Chemical (General).

Within each section, the documents are subcategorized by the source (company, agency, or organization) which authored them. This subcategorization was selected in order to help the reader obtain any documents he may wish, directly from the source responsible for them. This is especially helpful in the cases of papers authorized by an organization for either publication separately, as part of a conference, or within a journal. All documents in these subcategories are then arranged alphabetically by title.

Note: All bibliographic citations that are followed by an asterisk (*) refer to documents that were obtained in performance of this contract.

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